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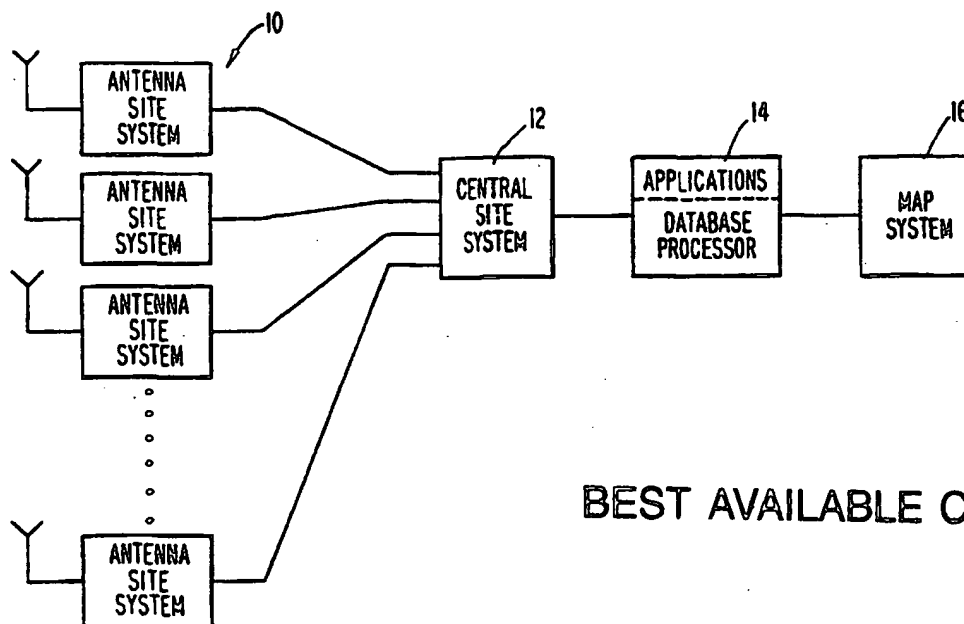
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(57) Abstract

A system for determining the location of a mobile transmitter is disclosed. The mobile transmitter receives a message signal and responds to the message signal by transmitting a responsive signal, wherein the responsive signal is indicative of the identity of the mobile transmitter. One preferred embodiment comprises at least three antenna site systems (10), a central site system (12), a database processor for use in connection with various applications, and a map system (16). The system may be employed to locate cellular telephones and/or like devices emitting bursty transmissions, e.g., over messaging or control channels.

SYSTEM FOR LOCATING A SOURCE OF BURSTY TRANSMISSIONS

CROSS REFERENCE TO RELATED APPLICATION

5

FIELD OF THE INVENTION

The present invention relates generally to methods and apparatus for locating the source of a radio transmission. More particularly, the present invention

10 relates to a system for locating a transmitter that transmits and receives "bursty" messages having a duration on the order of a few seconds or less, and often a few hundred milliseconds or less. Specific embodiments of the present invention may be used to locate transmitters used in analog

15 or digital cellular systems, personal communication networks (PCNs), enhanced specialized mobile radios (ESMRs), cellular digital packet data (CDPD) networks, and two-way packet-based data networks, such as RAM Mobile Data and Ardis networks. Although such transmitters employ different signal structures

20 and operate in different frequency bands as assigned by the Federal Communications Commission (FCC), the invention disclosed herein may be practiced in connection with any of these transmitters and with international variants thereof.

BACKGROUND OF THE INVENTION

25 Preferred embodiments of the present invention may be used to locate the standard transmitters used in a variety of communications networks. A "standard" transmitter is one which is generally used in the network and has not been

-2-

specially designed or modified to make it easier to locate.
For example, standard transmitters of the type mentioned
above share two common characteristics.

First, they are intended to be mass marketed and
5   thus inexpensive. To this end, they employ low cost
transmitter and receiver circuitry. Such mass marketable
transmitters are distinguished from more expensive
transmitters designed specifically for use with a locating
system. An example of the latter is disclosed in U.S. Patent
10 No. 5,218,618, June 8, 1993, titled "Cellular Telephone
Service Using Spread Spectrum Transmission," which discloses
a system employing a special type of spread spectrum
transmitter to be deployed in vehicles.

Second, each of the transmitters mentioned above
15 employs a messaging channel that carries a bursty data
transmission (as distinguished from a voice transmission or a
circuit switch data transmission). The expression "messaging
channel," as used herein, refers to one or more radio
channels carrying two way communications between a first and
20 a second radio transmitter (where either the first or the
second radio transmitter is the transmitter to be located),
wherein the communications include (1) commands and responses
between the first and the second transmitters; and (2)
information identifying at least one of the first and second
25 transmitters. For example, a cellular telephone system's
control channels are examples of "messaging channels." A
CDPD system is a messaging system overlaid on a cellular
system. Thus, the portion(s) of a cellular system's spectrum
normally assigned to voice conversations may also be
30 considered a messaging channel when carrying CDPD data packet
transmissions. For further background on the present
invention, the reader is referred to the above-cited U.S.
Patent Application Serial No. 08/059,248. In addition,
reference may be made to U.S. Patent Application Serial No.
35 08/105,506, filed August 11, 1993, "Methods and Apparatus for
Increasing the Efficiency of a Cellular Telephone Location
System."

SUMMARY OF THE INVENTION

One goal of the present invention is to provide a
system capable of locating the source of bursty
transmissions, as opposed to continuous transmissions of the
5   kind associated with voice conversations. Systems that
require a continuous transmission, such as a voice channel
transmission or a so-called circuit switch data transmission,
require the extended use of expensive radio channel capacity,
and are not practical. A further goal of the present
10   invention is to provide a system capable of locating a
standard transmitter that has not been specially designed or
altered to provide signals making the transmitter easy to
locate. The present invention achieves these goals by
applying the invention disclosed in U.S. Patent Application
15   Serial No. 08/059,248 to the location of standard
transmitting devices that are similar but not necessarily
limited to cellular telephones. Generally, the invention
achieves these goals by processing the brief, bursty
transmissions normally transmitted at periodic intervals or
20   in response to a message signal (e.g., a page). Typically,
the bursty response contains information about the identity
of the responding transmitter.

One exemplary application of the present invention
involves locating packages in transit, wherein the packages
25   carry a small transmitting device like a cellular telephone
but not capable of voice communication. In this example, the
transmitter would only receive pages and respond by
transmitting a signal identifying itself and/or the package
in transit with which it is associated. The transmitter
30   could be a cellular telephone whose voice capability is not
used, a PCN transmitter whose voice capability is not used,
or a CDPD device designed for data transmission.

In sum, the present invention provides a process
and a system for determining the location of a "standard"
35   mobile transmitter not specifically designed or altered to
provide signals facilitating the location of the transmitter.
In one preferred embodiment of the invention, the standard

-4-

mobile transmitter is operative to receive a message signal
and to respond to the message signal by transmitting a bursty
responsive transmission indicative of the identity of the
standard mobile transmitter. The inventive process comprises
5   the steps of receiving the bursty responsive transmission
from the standard mobile transmitter at (at least) first,
second, and third antenna sites; digitalizing the received
bursty responsive transmission at each of the antenna sites;
determining first, second, and third time differences of
10 arrival; and estimating the location of the standard mobile
transmitter on the basis of at least the time differences of
arrival. The first time difference of arrival represents a
difference between the time of arrival of the responsive
transmission at the first and second antenna sites.
15 Similarly, the second time difference of arrival represents a
difference between the time of arrival of the responsive
transmission at the first and third antenna sites, and the
third time difference of arrival represents a difference
between the time of arrival of the responsive transmission at
20 the second and third antenna sites.

        In presently preferred embodiments, the standard
mobile transmitter is a cellular telephone transmitter, a
personal communication network (PCN) transmitter, an enhanced
specialized mobile radio (ESMR) transmitter, a cellular
25 digital packet data (CDPD) transmitter, or a two-way packet-
based data transmitter. Furthermore, in preferred
embodiments the bursty responsive transmission is received
over a messaging channel, which may be, e.g., a control
channel of a cellular system.

30   Those skilled in the art will recognize that
extremely difficult technological challenges must be overcome
in developing a practical process and system for locating a
standard mobile transmitter on the basis of bursty
transmissions. For example, these challenges relate to the
35 difficulties involved in receiving bursty transmissions and
separating these transmissions from each other and from other
electromagnetic interference, including interference

resulting from multipath. Moreover, the problems involved in identifying the times of arrival of a particular transmission at the respective antenna sites are great. Disclosed herein are a variety of inventive signal processing techniques for

5   overcoming these problems. For example, in presently preferred embodiments, the step of estimating the position of the mobile transmitter comprises making a coarse estimate by creating a grid of possible latitude and longitude positions for each antenna site pair; calculating theoretical time

10 difference of arrival values for pairs of antenna sites; determining a function of a sum of squares of the measured time differences of arrival minus the computed time differences of arrival; and coarsely estimating the position as the point at which the function of the sum of squares is a

15 minimum. The coarse estimation step preferably includes deriving quality factors representing the quality of the signal received at the antenna sites of the pairs. In one preferred embodiment, the step involving determining a function of the sum of squares includes weighting the squares

20 of the measured time differences of arrival minus the computed time differences of arrival by the quality factor. In addition, preferred embodiments include providing a confidence interval along with the location estimate. The confidence interval defines an area around the estimated

25 location in which there is a probability the mobile transmitter is located.

        In addition, preferred embodiments comprise the steps of determining first, second, and third frequency differences of arrival; and estimating the velocity of the

30 standard mobile transmitter on the basis of at least the frequency differences of arrival. In presently preferred embodiments, the step of estimating the velocity of the mobile transmitter comprises making a coarse estimate by creating a grid or table of possible velocities; calculating,

35 for pairs of antenna sites, theoretical frequency difference of arrival values corresponding to the possible velocities; determining a function of a sum of squares of the measured

-6-

frequency differences of arrival minus the computed frequency
differences of arrival; and coarsely estimating the velocity
as the velocity at which the function of the sum of squares
is a minimum.

5   Preferred embodiments also include generating a
timing signal at each antenna site and using the timing
signal as a reference in determining the time differences of
arrival. The generation of the timing signal may include the
steps of receiving a global positioning system (GPS) signal
10 and generating a timing signal which is phase locked to the
GPS signal. Alternatively, the generation of the timing
signal may include the steps of transmitting a modulated
carrier from a central site. The modulated carrier
preferably has a carrier frequency near the frequency of the
15 responsive signal. This embodiment also involves receiving
the modulated carrier at each of the antenna sites and using
the modulated carrier as a reference signal for the
generation of the timing signal. The modulation of the
modulated carrier transmitted from the central site
20 preferably comprises a repetitive bit sequence having a
repetition period greater than the greatest time difference
of arrival expected to be encountered. For example, the
modulation may include a pseudorandom bit sequence having a
repetition rate greater than the greatest timing delay or
25 time difference of arrival expected to be encountered.

In a presently preferred embodiment, the generation
of the timing signal includes the steps of transmitting a
reference signal from a plurality of reference transmitters,
with each reference transmitter being visible to a
30 corresponding pair of antenna sites. The reference signals
are received at the respective antenna sites of each pair and
used at each antenna site in each pair in generating a timing
signal having a frequency and phase matched to the frequency
and phase of the timing signal of the other antenna site in
35 that pair. Preferably, the timing signal at each antenna
site is an oscillating digital signal and is mixed with the

-7-

digitalized responsive transmission or a downconverted
version thereof to produce a baseband signal.

In preferred embodiments, the reception and
processing of the responsive signal at each antenna site
5   comprises receiving the responsive signal with an antenna
array at each antenna site, and providing a high quality
signal (preferably, a single high quality signal) for further
processing. The step of providing a high quality signal
comprises sampling a signal from each antenna in the array
10   and formatting the samples into frames of digital data. On
the basis of the frames of data, a high quality digital
baseband signal is provided for further processing.
Preferably, the process also includes determining whether the
respective signals received via the antennas of the array
15   contain a prescribed level of energy, and only providing a
baseband signal for those signals having the prescribed level
of energy or greater. In preferred embodiments, each data
frame comprises a prescribed number of data bits and time
stamp bits that represent the time at which the responsive
20   signal was received. Furthermore, the high quality baseband
signals are preferably provided at the respective antenna
sites by coherently combining multiple baseband signals so as
to reduce the effects of multipath. Preferred embodiments
reduce the effects of multipath at each antenna by detecting
25   a first leading edge of the responsive signal and rejecting
subsequent leading edges of the responsive signal.

One presently preferred embodiment of the invention
includes the steps of: (1) generating a substantially
unimpaired representation of the baseband signal by
30   remodulating the demodulated signal; (2) determining which
antenna in the array likely received the transmission over
the shortest and most direct path; (3) performing a
correlation between the generated, unimpaired representation
of the signal and each of the signals received through each
35   of the antennas, and generating a correlation output function
for each signal; (4) determining the relative amount of
multipath impairment that may have occurred at each antenna

-8-

by measuring the width of each correlation output function at a predefined point on the correlation output function; (5) coherently combining the signals that appear to have similar multipath impairments to increase the quality of the signal

5 representation; and (6) estimating a quality factor that is indicative of the relative amount of impairment that will remain in the signal after processing.

Preferred embodiments also include extracting selected signal characteristics from the high quality

10 baseband signal; compressing the high quality baseband signal so as to retain the selected characteristics; and forwarding the compressed signal to a prescribed location for further processing. The selected characteristics preferably include timing, power, frequency, phase, and a factor representing

15 the quality of the baseband signal.

In presently preferred embodiments of the invention, the time and frequency differences of arrival are determined simultaneously using a maximum likelihood estimator. For example, the maximum likelihood estimator

20 preferably involves finding the peak of a function R_{x1x2} defined as,

$$R_{x_1 x_2}(\tau, \Omega) = \left| \int_{-\infty}^{\infty} X_1(t-\tau) \, X_2^*(t) \, e^{-i\Omega t} dt \right|$$

where $X_1(t)$ and $X_2(t)$ are the complex envelopes of the signals received at the respective antenna sites of a pair, τ represents the delay, Ω represents Doppler shift, t

25 represents time, and ω_0 represents the frequency of the responsive signal. The function R_{x1x2} defines a three-dimensional surface having a peak at a point where τ equals the time difference of arrival (TDOA) and Ω equals the frequency difference of arrival (FDOA). Thus, the TDOA and

30 FDOA are determined simultaneously by finding the peak of R_{x1x2}. Preferred embodiments also employ the maximum likelihood estimator to estimate and correct for chirp.

-9-

In addition, preferred embodiments demodulate the responsive signal received at each antenna site, determine the identification of the mobile transmitter, and, on the basis of the identification, decide whether to further
5   process or discard the responsive signal. Preferably, a table indicating which transmitters are to be located and which transmitters are not to be located is stored in a database. Thus, the location system may be implemented such that only subscribers to the system will be located.
10   The location estimation process also preferably involves dynamically selecting the best data from all data generated by processing data from the antenna site pairs. Preferably, the dynamic selection involves creating a table with data from all available antenna site pairs and then
15 ranking the antenna site pairs in accordance with appropriate criteria. Preferred embodiments determine identification bits, a channel number, and a time stamp for a signal obtained at each antenna site, and the dynamic selection comprises dynamically organizing the data according to the
20 identification bits, channel number, and time stamp.
          Presently preferred embodiments of the invention include storing location, velocity, and identification information in a remotely and locally accessible database. Preferably, the database allows storing, sorting, purging,
25 and archiving of the information. Preferred embodiments also include preventing unauthorized access to the location and identification information in the database. The data in the database may also be transformed into formats compatible with other applications, e.g., an electronic mapping application.
30   Preferred embodiments of the invention also include performing a calibration involving receiving, at multiple antenna sites, signals from a reference transmitter at a known location. Measurements are then performed among pairs of antenna sites to determine systemic errors that may exist.
35 Preferably, the calibration produces a site bias for use in location and speed calculations.

-10-

Preferred embodiments may also include performing the following functions:

(1) Merging the location data with billing data for the mobile transmitter, and generating modified billing data. In these embodiments, the billing data indicates the cost for each transmission made by the transmitter within a certain time period, the cost being based upon one or more predetermined billing rates. The modified billing data is based upon a different rate for calls made from one or more prescribed locations.

(2) Transmitting a signal to a selected mobile transmitter to cause the selected transmitter to transmit, thus allowing the system to locate the transmitter at any time (unless it is turned off).

(3) Automatically sending location information to a prescribed receiving station in response to receiving a distress signal from a mobile transmitter. This function allows emergency assistance to be provided to a subscriber in distress.

(4) Comparing the current location of a given mobile transmitter with a prescribed range of locations and indicating an alarm condition when the current location is not within the prescribed range.

(5) Detecting a lack of signal transmissions by a given mobile transmitter and in response thereto automatically paging the given transmitter to cause the given transmitter to initiate a transmission. Alternatively, instead of or in addition to paging the transmitter, an alarm condition may be communicated so that appropriate action can be taken.

(6)   Estimating a time of arrival of a given
        transmitter at a prespecified location.

(7)   Locating an object or person carrying a mobile
        transmitter.

5   (8)   Determining whether the estimated location is
              a feasible location and, if not feasible,
              setting or "snapping" the estimated location
              to the nearest feasible location.

(9)   Determining a feasible location area, or
10   "Virtual Location Area," for the mobile
              transmitter and sending messages to the
              transmitter only from antenna sites covering
              the Virtual Location Area.

        Another embodiment of the present invention
15 provides a system for determining the location of a
    "standard" mobile transmitter, wherein the system comprises
    at least three antenna site systems, a central site system,
    and means for determining the location of the mobile
    transmitter on the basis of the times of arrival differences.
20 In this embodiment, the antenna site systems include an
    antenna or antenna array; a sampling subsystem for sampling
    the bursty responsive signal and formatting the sampled
    signal into frames of digital data, with each frame
    comprising data bits and time stamp bits; a baseband
25 convertor providing baseband signals derived from the frames
    of data; and a timing subsystem. In presently preferred
    embodiments, the central site system comprises a maximum
    likelihood estimator for determining time differences of
    arrival and frequency differences of arrival. Preferred
30 embodiments also include location estimation means for
    creating a grid of theoretical points covering a prescribed
    geographic area; calculating theoretical values of time delay
    for a plurality of pairs of antenna sites; calculating a
    least squares difference value based on the theoretical time
35 delays and measured time delays for a plurality of pairs of
    antenna sites; searching the entire grid of theoretical
    points and determining the best theoretical latitude and

-12-

longitude for which the value of the least squares difference
is minimized; and starting at the best theoretical latitude
and longitude, performing another linearized-weighted-least-
squares iteration to resolve the actual latitude and
5   longitude to within a prescribed number of degrees or
fraction of a degree. The step of calculating theoretical
values of time delay preferably accounts for any known site
biases caused by mechanical, electrical, or environmental
factors, where the site biases may be determined by
10 periodically calculating the positions of reference
transmitters at known locations.

        Another embodiment of the invention provides a
method for determining the location of a mobile transmitter
transmitting a responsive signal over a predefined
15 "messaging" channel. The responsive signal is preferably
indicative of the identity of the mobile transmitter. The
method includes the steps of receiving the signal at at least
three separate ground-based antenna sites; processing the
signal at each antenna site to produce frames of data;
20 processing the frames of data to identify the responsive
signal and the differences in times of arrival of the
responsive signal among the antenna sites; and determining,
on the basis of the times of arrival differences, the
location of the mobile transmitter. Other features of the
25 present invention are described below.

BRIEF DESCRIPTION OF THE DRAWINGS

        Figure one is a schematic diagram of a mobile
transmitter location system in accordance with the present
invention.
30   Figure two is a block diagram of one preferred
embodiment of an antenna site system in accordance with the
present invention.

        Figure three is a more detailed diagram of a
portion of the antenna site system.

-13-

Figure 4 is a block diagram of one preferred embodiment of a central site system in accordance with the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS
5   I.   Overview of Location System

As described above, the present invention provides a system for determining the location of a mobile transmitter operative to receive a message signal and to respond to the message signal by transmitting a responsive signal (e.g.,
10 over a predefined message channel), wherein the responsive signal is indicative of the identity of the mobile transmitter. As shown in Figure 1, one presently preferred embodiment of the invention comprises at least three antenna site systems 10, a central site system 12, a database
15 processor for use in connection with various applications (discussed below), and a map system 16. The antenna site systems 10 may be collocated with cellular system cell sites, although this is not a requirement. For example, the antenna site systems may be positioned on top of a building or tower
20 where no other cellular equipment resides. As discussed above, the invention may be employed to locate cellular telephones and/or like devices emitting bursty transmissions, e.g., over messaging or control channels.

Preferred embodiments of the invention make
25 significant use of digital signal processing techniques. These techniques entail the use of appropriate forms of sampling and conversion hardware to convert analog radio frequency signals into sampled digital data forms. These techniques are widely known in the art, and are capable of
30 performing many functions traditionally implemented using analog components. The advantage of using digital signal processing include better control of noise during conversion, sampling, and filtering; and exact replication of these functions from antenna site to antenna site. With analog
35 components, variability of the components, even within tolerances, can cause different results at different antenna

sites. Since many of the subsystems process digital forms of
signals, it is technically immaterial whether many of the
subsystems reside at one or more of the antenna site
locations or instead reside at the central site location.

5 Therefore, the combination of all antenna sites and the
central site should be viewed as a network of signal
processing capability. Moreover, one skilled in the art will
recognize that it possible to rearrange certain subsystems so
that some functions described as being part of an antenna

10 site system may be moved to the central site system, and vice
versa. Indeed, in a commercial implementation of a location
system for a particular city, the actual location of
subsystems is a cost tradeoff involving the cost of digital
signal processing subsystems and the cost of communications

15 facilities connecting the antenna sites and the central site.

II.   **Antenna Site Systems 10**

Referring to Figure 2, each antenna site system 10
comprises an elevated ground-based antenna array for
receiving the responsive signal "over the air" with an array

20 of one or more antennas and allowing the antenna site system
to select the signal with the highest quality for further
processing. In addition, in preferred embodiments, each
antenna site system includes two or four sampling subsystems
10-1 for sampling the responsive signal from each antenna at

25 a prescribed sampling frequency using a prescribed sampling
algorithm and formatting the sampled signals into frames of
digital data. Each frame of data comprises a prescribed
number of data bits and time stamp bits that represent the
time at which the responsive signal was received. Two or

30 four baseband convertors 10-2 receive the sampled signal and
provide a baseband signal derived therefrom. A
multi-antennae processing subsystem 10-3 combines and
distinguishes the signals received from the individual
antennas in the antenna array, and then provides a single

35 representation of a signal for further processing. A
demodulating subsystem 10-4 determines the demodulated data
content of the responsive signal, where the demodulated data

content may include information identifying the mobile
transmitter and other user data conveyed in the responsive
transmission. A database subsystem 10-5 determines how and
whether a responsive signal should be further processed, or
5 whether it should be discarded. A signal processing
subsystem 10-6 extracts selected signal characteristics from
the frames of digital data, such as timing, power, frequency
and phase. A data reduction and forwarding subsystem 10-7
selects and compresses the data frames before transmission
10 over communications facilities to the central site 12 (Fig.
1). A timing subsystem 10-8 determines a timing signal
common to all antenna site systems. A calibration subsystem
10-9 performs self-calibration on the antenna site system to
determine and correct systemic changes in delay, frequency,
15 and phase of the various antenna site components. Finally,
an antenna site controller 10-10 exchanges commands with each
subsystem in the antenna site and the central site, and
controls the operation of the entire antenna site system.
The components/subsystems of the antenna site system are
20 described in greater detail below.

Antenna Array

In presently preferred embodiments of the
invention, the elevated antenna array located at each antenna
site includes an array of two or four antennas mounted on an
25 elevated platform, such as a tower or an appropriate point on
a building, where each antenna is suitable for receiving the
responsive transmissions. Omnidirectional antennas are
preferred, since they permit each antenna site system to
receive signals from the widest possible area. However,
30 directional antennas will also work, although their
visibility is limited. The antennas are preferably high-gain
antennas since the location system benefits from having as
many antenna site systems as possible viewing a particular
transmission. A high gain antenna mounted on a tower can be
35 expected to detect transmissions at distances of greater than
35 miles. It may also be possible to employ existing

antennas, such as the existing cellular omnidirectional
antennas at a cell site.

A preferred antenna array has two antennas located
in the same horizontal plane or four antennas with two in the
5   same vertical plane and two in the same horizontal plane
(arranged as a cross). In either configuration, the antennas
are spaced at a distance from each other that is greater than
one wavelength of the carrier frequency of interest. (For
example, if the system is to detect cellular transmissions,
10   then the carrier frequency would be near 834 MHz and the
wavelength would be about 35.97 centimeters.) If costs do
not permit the use of multiple antennas at each antenna site,
the antenna site systems, or a subset of the antenna site
systems, may be constructed with one antenna, although there
15   would be a degradation in the ability of the system to reject
multipath. Multipath is an impairment whereby multiple
copies of a single transmission are received at the antenna
site, where each copy of the transmission has traversed a
different path from the originating transmitter to the
20   antenna.

The purpose of an antenna array is to provide
horizontal and/or vertical antenna diversity at each antenna
site subsystem. The responsive signal transmissions that the
location system detects and processes are subject to
25   degradation from multipath and other interference. With
multiple antennas, the multi-antennae processing subsystem
10-3 measures the signal characteristics of the responsive
signal received by each of the antennas at the antenna site.
The multi-antennae processing subsystem compares each of the
30   measured signal characteristics, selects the signal with the
best characteristics, and routes this signal to the
transmission demodulation subsystem 10-4 and signal
processing subsystem 10-6.

Sampling Subsystem 10-1

35   Each sampling subsystem 10-1 is responsible for
converting a responsive signal from its analog or RF state
into a digital state at a particular intermediate frequency

-17-

(IF) using a prescribed sequence of steps. The digitalized
signals are represented by frames of digital data. For
example, for a cellular transmitter, this may involve
conversion from a carrier frequency of approximately 834 MHz
5 down to approximately 2 MHz. The sampling and baseband
convertor sections 10-1, 10-2 are especially important
because of the need to preserve the integrity of the
responsive signal throughout the down conversion process
without introducing additional noise or causing other
10 degradation or deterioration.

In considering the importance of the sampling and
baseband convertor sections, the narrowband nature of the
signals involved should be noted. For example, typical
cellular transmissions, whether related to analog or digital
15 voice cellular, CDPD, or the like, are channelized into
discrete channels of varying widths. For many cellular
transmitters, the messaging channel transmissions use a
reverse control channel, with all transmissions occurring in
one of 21 consecutive channels, each 30 kHz wide.
20 Mathematical studies of the nature of RF signals demonstrate
that narrowband signals are more susceptible to noise than
wideband signals, especially with respect to accurate timing
of the signals. In preferred embodiments of the present
invention, the sampling and baseband convertor subsystems are
25 designed to work under the worst case scenario of many
adjacent channels.

Referring to Figure 3, one preferred embodiment of
a sampling subsystem 10-1 comprises a connection to an
antenna 100 in the antenna array; a software-controlled,
30 variable amplifier 102 of sufficient gain to compensate for
cable loss and other communication channel losses; a first
low delay bandpass filter 104 with a bandwidth covering the
full expected transmission range of the mobile transmitters
(if these are cellular telephones, the bandwidth would be 21
35 channels x 30 kHz per channel = 630 kHz); a first high
stability, high accuracy crystal oscillator (OSC1) 106 and a
mixer 108 for transforming the RF signal down to a first

-18-

intermediate frequency IF1; a second low delay bandpass
filter 110 with a bandwidth similar to the first filter 104;
a second high stability, high accuracy crystal oscillator 112
(OSC2) and a mixer 114 for transforming the first

5   intermediate frequency IF1 to a second intermediate frequency
IF2; a third low delay bandpass filter 116 with a bandwidth
similar to the first filter 104; and a sampling circuit 118.
The intermediate frequencies IF1 and IF2 are selected so
that, through both stages of mixing and bandpass filtering,

10 no alias of the original signal is created at or near the
intermediate frequencies IF1 and IF2. Any aliases should
appear far enough away such that inexpensive bandpass filters
can be used. The second intermediate frequency IF2 should be
chosen such that the sampling circuit 118 can be built with a

15 readily available analog to digital convertor (A/D) that has
a sufficient dynamic range to adequately sample the signal.
For cellular signals, the dynamic range should be greater
than about 80 dB.

        The sampling circuit 118 comprises three main

20 components (not shown): (1) a software controlled, variable
gain amplifier used to adjust the level of the signal; (2) an
analog to digital convertor that samples the second
intermediate frequency IF2 at a prescribed sampling clock
frequency S1 using a prescribed number of sampling bits; and

25 (3) a digital buffer capable of temporarily storing the data
bits output by the A/D convertor before these bits are
forwarded to the baseband convertor 10-2. As mentioned, the
A/D convertor should have a sufficient dynamic range to
adequately sample the signal over its full expected signal

30 level. The sampling frequency S1 should be much greater than
the Nyquist rate (2 x IF2) plus the bandwidth of the signal.
For example, the frequencies used in connection with a
cellular system might be a second intermediate frequency IF2
of 2 MHz and signal bandwidth of 630 kHz. For such a system,

35 S1 should be much greater than 4.63 MHz. At the completion
of the sampling process, the signal is fully represented in a
digital form. All further processing in all other subsystems

-19-

takes place digitally and, therefore, uniformly across all
antenna site locations.

Baseband Convertor 10-2

        Each baseband convertor subsystem 10-2 is
 5 responsible for sequentially extracting and outputting a
    single baseband representation of a transmission received
    over one of the. narrowband channels by the antenna site
    system.   Each antenna site system preferably has two or four
    baseband convertor subsystems, each being connected to its
10 own antenna in the antenna array, through its own sampling
    subsystem 10-1. With this configuration, each baseband
    convertor extracts a baseband representation of a
    transmission as received by a single antenna. Later, the
    transmissions from the separate baseband convertors are
15 compared and combined.

        The baseband convertors 10-2 may be implemented
    with digital signal processing technology to improve the
    noise performance of the system, and to improve filter
    characteristic matching from one antenna site system to
20 another. In other words, it is desirable for the
    amplifier/filter sections to be matched with minimal
    variability between antenna site systems.

        Referring to Figure 3, presently preferred
    embodiments of the baseband convertors comprise a digital
25 signal processing subsystem 120 and software that emulates
    various functions traditionally implemented using hardware
    components. Specifically, the following functions are
    performed:

        (1)   the generation of complex signals including
30   the sine and cosine (in phase and quadrature)
              versions of a specific frequency, said signals
              being generated for the purpose of mixing the
              digitally sampled signals;

        (2)   the mixing of the digitally generated complex
35   signals with the digitally sampled
              transmissions received from the sampling
              subsystem 10-1 to generate further

-20-

intermediate signals and complex baseband
signals that represent only a single channel;

(3)   the lowpass and bandpass filtering of the
mixed signals, using an appropriate bandwidth
and filter characteristic to remove unwanted
signal components that result from mixing;

(4)   the performance of fast fourier transforms to
detect the presence or absence of power in
each of the channels in which transmissions
may occur; and

(5)   the coding of the digital bits to convey
timing and channel information to further
processes within the antenna site system and
the central site system.

The following example illustrates the processing
that might take place within the baseband convertor 10-2 to
extract a single cellular transmission occurring on reverse
control channel number 8. First, the baseband convertor
subsystem 10-2 receives a 100 millisecond segment of digital
bits from the sampling subsystem 10-1. The 100 millisecond
segment represents 630 kHz of signal bandwidth at the
intermediate frequency IF2. The baseband convertor digitally
generates a complex sinusoid OSC3, centered at frequency IF2,
and then digitally mixes OSC3 with the signal received from
the sampling subsystem. After mixing, the resultant signal
is appropriately bandpass filtered. This mixing generates a
baseband signal, at a frequency IF3, containing all 21
reverse control channels, each with a bandwidth 30 kHz. This
baseband signal is digitally stored because recursive
processing may be needed in the following stages for
simultaneous transmissions and each stage of processing
should begin with the unaltered representation of the
baseband signal. The baseband convertor subsystem 10-2 then
performs a fast fourier transform (FFT) on each of the
channels to detect whether a transmission occurred during the
time interval represented by the digital bits currently being
processed. In this example, the baseband convertor may

detect energy in channel number 8, and possibly other
channels, and decide to further process channel number 8.
The baseband convertor digitally generates a complex sinusoid
OSC(ch8), and then digitally mixes OSC(ch8) with the baseband

5   signal at IF3. This mixing, in combination with digital
filtering similar to that performed in earlier stages and
decimation of the samples, converts the reverse control
channel signal to a signal having a bandwidth of 30 kHz and
centered at 0 Hz. This final signal is represented by a set

10 of digital bits of length (T * R * S), where T is the
transmission length of the message, R is the sampling rate of
a single channel's baseband signal, and S is the sampling
resolution of the sampling subsystem. In this example, T is
100 milliseconds, R is 60 kHz or more, and S is 16 bits.

15 Therefore, in this example, the baseband convertor outputs 96
kbits plus the time stamp and channel identification bits to
further processing stages in the antenna site system and
central site system. If the sampling rate R were greater
than the Nyquist rate of 60 kHz, the number of bits output

20 would also be greater. If the FFT had detected energy in
other channels, say channels 11 and 23, the baseband
convertor would similarly process these channels and output a
similar set of 96 kbits.

        The signals OSC3 and OSC(ch8) are digitally

25 generated by the digital signal processing subsystem 120, and
therefore may be at any desired frequency. As discussed
below, one preferred implementation of the timing subsystem
10-8 (Fig. 1) involves the calculation of frequency and phase
errors between timing sources at pairs of antenna site

30 systems. The baseband convertor subsystem 10-2 calculates
the exact frequency and phase of OSC3 and OSC(ch8) by using
nominal starting values and then using adjustments supplied
by the timing subsystem.

Multi-Antennae Processing Subsystem 10-3

35   The multi-antennae processing subsystem 10-3 (Fig.
2) is responsible for combining and distinguishing the
digital representations of a single responsive transmission

as received by either two or four baseband convertor subsystems 10-1. The reader is reminded that RF transmissions typically reflect off of many surfaces, such as hills and mountains, buildings, metal structures, automobiles

5 and trucks, etc. Because of such reflections, a single transmission may be received at a particular antenna multiple times. This phenomenon is known as multipath. Each copy of the transmission will likely have taken a different path. Greater path lengths result in greater transmission times.

10 For example, if a single transmission takes three transmission paths of lengths L1, L2, and L3, where L3 > L2 > L1, the transmission or propagation times T1, T2, and T3 will exhibit the relationship, T3 > T2 > T1. However, the relationship between power levels of the three signals as

15 received at an antenna P1, P2, and P3 will be indeterminable. One cannot even assume the relation P1 > P2 > P3, although this may frequently be the case. The exact amount of multipath impairment cannot be exactly determined from the received signal. However, the amount of signal impairment

20 can be estimated from the change in the width of the received signal from its estimated original transmitted state, and from variations in the envelope of the received signal. Moreover, it is known that the envelope of a transmitted cellular signal is constant.

25   The antenna array is constructed with two or four antennas spaced at distances greater than one wavelength because it can be shown that the RF propagation paths can be very different at positions separated by one wavelength or greater. The separation of a set of antennas designed to

30 receive the same signal is known as "antenna diversity." In preferred embodiments of the present invention, the antenna array associated with each antenna site system incorporates both horizontal and vertical antenna diversity. Each of the antennas receives the responsive transmission via a different

35 path. These responsive transmissions, which may be impaired differently by the effects of multipath or other aberrations, are separately processed by separate sampling subsystems 10-1

-23-

and separate baseband convertor subsystems 10-2. These
subsystems receive a common clock from the timing subsystem
10-8. Any differences in electrical path length from the
timing subsystem to the respective subsystems receiving the
5 clock are compensated (e.g., in the digital signal processor
120) to substantially eliminate any variability among the
processing performed by the subsystems. Each baseband
convertor subsystem 10-2 then forwards its digital
representation of a single transmission to the multi-antennae
10 processing subsystem 10-3, which combines the two or four
representations of the transmission into a single
representation, with the maximum amount of multi-path and
other impairments removed from the signal.

    The multi-antennae processing subsystem 10-3
15 performs the following functions using digital signal
processing subsystems, taking into account the exact relative
physical locations of the mounted antennas at the antenna
site:

(1)   the demodulated data bits received from the
20   transmission demodulator subsystem 10-4 are
        remodulated at baseband so that an unimpaired
        representation of the signal is generated;

(2)   the relative time of arrival of the leading
        edges of each of the received transmissions is
25   measured to determine which antenna likely
        received the transmission over the shortest
        and most direct path;

(3)   a correlation is performed between the
        generated, unimpaired representation of the
30   signal and each of the signals received
        through each of the antennas;

(4)   the width of the correlation output function
        is measured at a predefined point on the
        correlation output function to determine the
35   relative amount of multipath impairment that
        may have occurred at each antenna;

-24-

(5)   the signals that appear to have exact or very
similar multipath impairments are coherently
combined to increase the quality of the signal
representation for later processing stages;

5   (6)   a quality factor that is indicative of the
relative amount of impairment that will remain
in the signal after processing is estimated,
the quality factor being akin to a statistical
confidence interval measure that will later be

10   used in the final location calculation; and

(7)   a single signal representation is output to
the signal processing subsystem 10-6.

The preferred characteristics of the single
representation provided to the signal processing subsystem

15 10-6 are: (a) it represents a coherent combination of signals
where possible; (b) envelope variations have been removed;
(c) phase and frequency have been faithfully maintained, and
(d) the timing bits reflect the measurement of the leading
edge of the responsive signal at the antenna array.

20 **Transmission Demodulation Subsystem 10-4**

The transmission demodulation subsystem 10-4 uses a
digital signal processing subsystem to demodulate the
responsive transmission at baseband.   The demodulation
technique used is selected based upon the modulation used for

25 the responsive transmission.   For example, the reverse
control channel of a cellular telephone is a 10 kbits per
second data stream that is first Manchester encoded and then
modulated using frequency shift keying (FSK) at frequencies
that are +/- 8 kHz around the center frequency of the

30 channel.   The transmission demodulation subsystem 10-4 uses
the digital baseband representation of the responsive signal
from one of the baseband convertors as its input, and then
outputs the actual digital content of the message without
modulation of any kind.   For example, the reverse control

35 channel transmission of a cellular telephone, which may have
required 100 milliseconds to transmit and may require 100
kbits to represent at baseband, may be represented by

approximately 100 bits after demodulation. The transmission
demodulation subsystem forwards the data bits and an error
count to the multi-antennae processing subsystem 10-3, the
database subsystem 10-5, and the signal processing subsystem

5   10-6. The error count is calculated based upon any known
error control built into the modulation protocol and the
demodulation of the received transmission. For example, some
modulation schemes used by cellular telephones repeat the
data bits multiple times to increase the likelihood of

10 accurate reception. Other modulation schemes include parity
bits or cyclical redundancy checks.

Database Subsystem 10-5

        The functionality residing within the database
subsystems 10-5 at the respective antenna site locations is

15 shared with the database subsystem 12-5 (Fig. 4) residing at
the central site 12. The database subsystems are primarily
responsible for storing the identification numbers and
appropriate security information, as well as other parameters
about the transmitters in use in the geographic area covered

20 by the location system. For example, in a system for
locating cellular telephones, the database subsystems would
store, for each cellular telephone in the geographic area
served by the location system, the phone number (or Mobile
Identification Number), the electronic serial number (ESN),

25 and appropriate codes. The codes would identify specific
location services and applications for which the phone has
been subscribed. Exemplary applications of the invention are
described below.

        Each database subsystem 10-5 receives the

30 responsive transmitter's demodulated data from the associated
transmission demodulation subsystem 10-4. The database
subsystem then extracts the transmitter's identification,
security information, and other address information from the
transmission, and uses that information to look up stored

35 codes in the database to determine a further course of action
for the received transmission. For example, codes in the
database subsystem may indicate that the customer does not

desire location services and the antenna site system may stop
further processing of the transmission, thereby conserving
processing resources. Other codes in the database subsystem
may indicate that the transmission should be completely

5 processed and forwarded to a particular application upon
completion of processing. Other codes may indicate, for
example, that, if a cellular telephone customer dials "911",
the transmission should be processed regardless of whether
the customer subscribes to location services and that the

10 result of the processing should be forwarded to the
appropriate "911" service center. It should be noted that
different "911" emergency service centers may serve different
cities, counties, or states, and that the database subsystem
preferably determines where to send the location information.

15 Other codes in the database subsystem may indicate whether
the current transmission originated from a reference or
calibration transmitter and, if so, the database subsystem
may notify the appropriate subsystem as necessary.

         Based upon the stored codes and the demodulated

20 data, the database subsystem can direct further activities
within the antenna site system 10. For example, in preferred
embodiments of the invention, the database subsystem
determines whether the multi-antennae processing subsystem
10-3, the signal processing subsystem 10-6, the timing

25 subsystem 10-8, and the calibration subsystem 10-9 should
continue processing the current transmission, or whether all
representations of the responsive transmission should be
discarded.

Signal Processing Subsystem 10-6

30   The functionality within the signal processing
subsystem 10-6 at each antenna site location is shared with
functionality within the signal processing subsystem 12-3
(Fig. 4) in the central site system 12. As discussed above,
the actual location of any specific software function and its

35 corresponding digital signal processing subsystem hardware is
an economic tradeoff and not a technical tradeoff.
Therefore, the complete description of the signal processing

is covered in the description (below) of the central site
system.

Data Reduction and Forwarding Subsystem 10-7

       The data reduction and forwarding subsystem 10-7
5 (Fig. 2) is responsible for receiving data frames from the
signal processing subsystem 10-6 and the antenna site
controller 10-10, compressing the data frames, and forwarding
the data frames in an error free manner to the central site
system 12 (Fig. 1). The compression of the data frames is
10 accomplished with knowledge of the structure of the
responsive transmissions and standard compression algorithms.
For example, cellular transmitters transmit using a constant
envelope. Therefore, amplitude information is redundant and
may be stripped by the compression algorithm, leaving only
15 phase information about the signal.

       Each data frame will typically contain the
following information:

          (1)   the demodulated bits of the responsive
               transmission and the error count;
20   (2)   the time stamp bits indicating the time of
               arrival of the leading edge of the
               transmission;
          (3)   the calculated quality factor associated with
               the responsive transmission;
25   (4)   the estimated power present in the signal
               transmission, as calculated by the FFT;
          (5)   the channel number in which the transmission
               was received, where the channel number is
               indicative of the received frequency prior to
30   conversion to baseband; and
          (6)   the digital representation of the responsive
               transmission.

Timing Subsystem 10-8

       The timing subsystem 10-8 at each antenna site
35 location is responsible for providing an accurate, stable
timing source. A preferred timing subsystem can provide
timing that is accurate to within 10 nanoseconds. That is,

the time as measured by each antenna site system 10 deviates
by no more than 10 nanoseconds from the time as measured by
the other antenna site systems. The timing subsystem 10-8
provides a reference frequency that is used to lock the
5 frequencies used to mix and sample the analog RF signal and
convert the signal into a digital data format.

In one preferred embodiment, the timing subsystem
includes a GPS receiver located at each antenna site
location. The GPS receiver is preferably a differential
10 receiver capable of correcting for changes in ionospheric or
atmospheric conditions and GPS satellite movements.
Preferably, the GPS receiver always outputs a pulse that is
within 10 nanoseconds of a pulse that is output by another
GPS receiver located at any of the other antenna site
15 locations within a given system. The differential
corrections may be accomplished through prior knowledge of
the GPS satellite epherimides and current ionospheric
conditions and by using standard algorithms to calculate
corrections. Alternatively, the corrections may be
20 accomplished through the transmission of a second signal such
that the GPS receiver can discriminate and determine
perturbations in the primary GPS signal versus the secondary
signal and then calculate corrections.

At each antenna site location, a local oscillator
25 that is both temperature controlled and voltage controlled is
used to drive a phase locked loop. Within the phase locked
loop, a pulse is created whose periodicity is the same as the
pulse output by the GPS receiver. The phase locked loop then
makes corrections to the oscillator to adjust the internally
30 generated pulse until it coincides with the GPS created
pulse. Phase locked loops will result in an oscillator
output IF1 and IF2 whose frequency and phase are well
controlled and locked at each of the antenna site locations
and between antenna site locations.

35 In another embodiment, the timing subsystem
includes a centrally located transmitter whose carrier
frequency is near the carrier frequency of the responsive

-29-

signal. The carrier frequency is modulated with a second
signal whose structure is conducive to timing extraction at
the various antenna site locations. Such a modulation signal
could be a pseudorandom bit sequence whose repetition rate is
5 much greater than the greatest timing delay expected in the
geographic area encompassed by the location system. For
example, if a location system were installed in a geographic
area measuring 100 miles across at its greatest dimension,
the maximum expected delay in the system would be 538
10 microseconds (100 miles/186,000 miles per second). If the
pseudorandom sequence repeated over a period greater than
this, such as one to two seconds, any receiver at an antenna
site could unambiguously determine the time of arrival of a
responsive signal relative to the nearest earlier start of
15 the pseudorandom sequence. In this preferred embodiment, the
centrally located transmitter transmits its signal
continuously. Each antenna site receives the signal emitted
by the centrally located transmitter using the same antenna
and cabling used for receiving the responsive signal. This
20 sharing of antenna and cabling causes atmospheric and
environmental perturbations to act simultaneously on both the
timing subsystem and the responsive signal, thereby
cancelling out the effect of the common mode perturbation at
that antenna site. The location of each antenna site is
25 known relative to the central site, and therefore a known
delay exists between the transmission of the timing signal at
the central site and its reception at each antenna site.
This known delay is applied during timing extraction such
that the calculated time at each antenna site is within 10
30 nanoseconds of that at each other antenna site. In this
embodiment, phase locked loops are employed in a manner
similar to those used in the GPS based embodiment.

In a third and most preferred embodiment, the
timing subsystem 10-8 includes a high stability, high
35 accuracy, free running local oscillator at each antenna site
location, and at least one reference transmitter situated in
a geographic location visible to at least two of the antenna

-30-

site systems 10. In this embodiment, any pair of antenna
site locations should be able to see the same reference
transmitter, but not all antenna site locations need to see
the same reference transmitter. In a given system

5   implementation, enough reference transmitters should be
located throughout the covered area to meet the pairwise
visibility guideline stated above. The reference transmitter
is preferably similar to the transmitters located by the
system. For example, it may simply be a cellular telephone

10   or a CDPD unit. The advantage of using a similar reference
transmitter is that the analog RF path taken by the reference
transmitter would be identical to that taken by all other
transmitters that are being located, and therefore common
mode perturbations would be cancelled. The reference

15   transmitter should be situated in a location that is open,
visible, and minimizes multipath between the reference
transmitter and antenna sites that the reference transmitter
serves. In this embodiment, no corrections are made to the
local oscillator itself. In other preferred embodiments, the

20   use of phase locked loops accomplishes the phase locking by
making phase adjustments to the local oscillator to correct
the local oscillator's phase and frequency to match that of
the timing source, such as the GPS receiver or the centrally
located timing transmitter. The phase locking technique

25   introduces the unwanted effect of adding new phase errors, or
phase noise, to the phase errors that are already present in
the free running oscillator.

In this embodiment, each antenna site system is at
a known location relative to the reference transmitter.

30   Therefore, the exact delay between the reference transmitter
and the antenna site is known. The reference transmitter is
known to be stationary and thus its Doppler shift is zero.
Therefore, for each pair of antenna site locations that
receives a signal from the reference transmitter, the

35   relative frequency and phase drift of the local oscillator at
one antenna site can be determined relative to the local
oscillator at the second antenna site. This determination is

accomplished by processing the reference transmitter signal
exactly the same as the processing of a responsive signal
from any other transmitter. If, during processing, a Doppler
shift is found between any pair of antenna sites, then that
5 Doppler shift must be due solely to the drift of the timing
source at one antenna site relative to the timing source at
the other antenna site. Because the oscillators drift only
around their nominal frequency, the rate and amplitude of the
drift can be well characterized by recording the pairwise
10 antenna site timing errors over time. The timing error
between any pair of antenna sites can then be predicted,
measured, and adjusted in later processing at any particular
instant in time.

        This preferred embodiment takes advantage of the
15 digital signal processing in other subsystems of the location
system. For example, in the baseband convertor subsystem 10-
2, the final mixing stage is accomplished digitally in
software, using a digitally synthesized intermediate
frequency whose frequency and phase can be completely
20 controlled in software. The relative frequency and phase
drift can be characterized as error terms in the digital
signal processing and, more importantly, in the digital
mixing stages. In this manner, timing is effectively locked
between antenna sites. Because this third method of timing
25 results in locked timing between antenna sites with the least
amount of frequency and phase noise, it is preferred over the
other timing schemes.

Calibration Subsystem 10-9

        The calibration subsystem 10-9 is responsible for
30 calculating the effects of various systemic errors in the
antenna site system, and then applying the results of these
calculations to the processing of the transmission(s)
received by the antenna site system 10. Systemic errors
occur due to fluctuations in the weather, including
35 temperature and humidity, in the temperature of the equipment
comprising the location system, or even in the power used by
the location system. The systemic errors can occur

-32-

periodically or randomly, and can effect changes in the
relative delays (propagation times) of signals through
communications paths in the antenna site system. These
delays generally occur while the responsive transmissions are

5 at an RF level. For example, the cable connecting an antenna
at the top of a tower to the antenna site system in a ground
based enclosure may become heated by the sun and experience a
variation in its normal signal delay characteristics.

A preferred embodiment of the calibration subsystem

10 10-9 is similar to the timing subsystem in that its operation
is based upon the installation of reference transmitters in
the geographic area served by the location system. Because
the reference transmitters are in known and fixed locations,
the theoretical delay measurements can be mathematically

15 determined. When the calibration subsystem 10-9 is notified
by the database subsystem 10-5 that a calibration
transmission is currently being processed, the calibration
subsystem will receive the results of the processing. Based
upon the present results, the results from recent historical

20 processing, and the theoretical delay values, the calibration
system will determine a site bias, or error term, for that
antenna site. The error term represents the present
accumulation of systemic errors from all sources. This error
term is used by the signal processing subsystems 10-4, 12-3

25 at the antenna site and the central site to adjust the delay
measurements calculated for all other responsive
transmitters. The error is also used by the position and
speed determination subsystem 12-4.

Antenna Site Controller 10-10

30   One presently preferred embodiment of the antenna
site controller 10-10 is a software based microprocessor
responsible for the orderly operation and maintenance of all
functions and subsystems in the antenna site system 10. The
antenna site controller can generate and receive commands

35 from all subsystems and the central site 12 via the
communications link that connects each antenna site to the
central site. For example, the antenna site controller may

update tables in the database subsystems 10-5 based upon
instructions from the central site.

III.   **Central Site System 12**

Referring to Figure 4, presently preferred
5 embodiments of the central site system 12 comprise a
reception means 12-1 for receiving transmissions from the
various antenna sites and decompressing the transmissions so
as to restore the original digital data frames that existed
prior to compression by the antenna site systems 10; a
10 dynamic selection and control subsystem 12-2 for determining
how data frames from various antenna sites will be processed;
a signal processing subsystem 12-2 for further processing the
data frames to generate data identifying the mobile
transmitter and the differences in times of arrival and the
15 differences in frequency of arrival of the responsive signal
among the antenna site systems; a position and speed
determination subsystem 12-4 for using the differences in
time of arrival and frequency of arrival to determine the
geographic location of a transmitter using a prescribed
20 geographic coordinate system, as well as the speed and
direction of travel of the transmitter; and a database
subsystem 12-5 for determining how the results of the
measurements and calculations performed by the various
subsystems should be used. The options for using the results
25 include storing the results, forwarding the results to other
applications for further processing, or discarding the
results.

Reception Means 12-1

The reception means 12-1 is responsible for
30 operation and maintenance of the communications links that
connect each antenna site system 10 to the central site
system 12 and the decompression of the data bits from a
compressed state to an original state fully representing the
responsive transmission. The communications links may be any
35 of a variety of standard links, such as copper, fiber optic,
or microwave links. The transmission speed of a
communications link is determined by the amount of traffic

-34-

that any particular antenna site receives and the
transmission delays that are acceptable to the subscribers of
the location service. For example, as discussed above, a
cellular telephone transmission over a reverse control
5 channel may generate approximately 100,000 bits prior to
compression at the antenna site. Compression may reduce this
by a factor of three to four, resulting in approximately
30,000 bits that must be sent over the communications link.
If the antenna site receives an average of one transmission
10 per second, the subscriber must use a communications link of
at least 30 kbps. If the antenna site typically receives
more than one transmission per second, the link speed
(bandwidth) must be increased proportionately.
Communications links typically offer speeds in increments of
15 56 kbps or 64 kbps, up to a "T1" speed of 1.544 Mbps. The
present invention may be practiced with any of these
transmission speeds.

        After receiving a data frame from an antenna site,
the data frame is decompressed using the inverse of the
20 algorithms used to compress the data at the antenna site
system 10. The restored data frames are then forwarded to
the selection and control subsystem 12-2. Preferably, the
reception means 12-1 is capable of simultaneously processing
data received via the communications links from all antenna
25 site systems 10. In a medium sized geographic area, there
may be 20 to 40 antenna sites connected to a central site.
In a large sized geographic area, there may be well over 100
antenna sites connected to a central site.

Dynamic Selection and Control Subsystem 12-2

30   The dynamic selection and control subsystem 12-2 is
responsible for determining which data frames from which
antenna site locations will be used by the signal processing
subsystem 12-3 to calculate the location of a responsive
transmitter. Since 20 to 40 antenna sites may be located in
35 a medium sized geographic area, any one responsive
transmission will likely not be received at all antenna
sites. Therefore, processing data frames from all antenna

sites is inefficient. Data frames are required from a
minimum of three antenna sites for trilateration or
triangulation. It is preferred to process data frames from
more than three antenna sites so that the location may be
5   overdetermined and the accuracy improved.

The dynamic selection subsystem 12-2 operates on
the basis of the stored knowledge of the location and
relative orientation of the antenna sites systems. When a
responsive transmission occurs, the transmission is typically
10 received at different power levels at the different antenna
sites. For example, if the transmitter is a cellular
telephone, the responsive transmission is generally received
at the highest power level at the antenna site collocated
with the cell site communicating with the cellular telephone.
15 Because power generally declines with the square of the
distance, more distant antenna sites will receive the signal
at lower power levels.

For a particular responsive transmission, the
dynamic selection subsystem 12-2 will receive data frames
20 from all antenna sites that have received the transmission.
The dynamic selection subsystem dynamically organizes the
data by matching all transmissions with the same
identification bits, channel number, and relatively close
time stamps. The reader should note that some transmitters,
25 such as cellular telephones, may emit several transmissions
over a short period of time. Therefore, because it is
possible that one antenna site system will miss a first
transmission but receive a second transmission, the
transmissions should be carefully organized by time so as to
30 discriminate the transmissions.

For all received transmissions identified as having
originated from the same transmitter, the dynamic selection
subsystem 12-2 compares the power levels, quality factors,
and error counts from the different antenna sites. Based
35 upon highest power level and lowest error count, the
subsystem identifies the likely closest antenna site to the
transmitter. Beginning with this first antenna site, the

subsystem then sequentially examines the data frames received
from each of the next closest antenna sites to identify the
second, third, fourth, etc., sites that should be used in the
subsequent signal processing. If data frames are received
5 from more than a threshold number of antenna sites, the
dynamic selection subsystem 12-2 examines the quality factors
and error counts to determine which data frames, if any, are
the best candidates for retention or exclusion. If the error
count of the data frames from a particular antenna site is
10 greater than a threshold value, 10 bits for example, that
data frame from that antenna site may be discarded. If the
quality factor of the data frames from a particular antenna
site is worse than a threshold value, 200% worse than the
average quality factor for example, that data frame from that
15 antenna site may be discarded. Preferably, the dynamic
selection subsystem 12-2 attempts to retain data frames from
at least the threshold number of antenna sites, unless the
error counts and quality factors are sufficiently poor from
antenna sites so as to mandate their exclusion even if less
20 than the threshold number of data frames remains. If the
dynamic selection subsystem cannot retain the data frames
from at least three antenna sites, the processing for this
transmission is discarded and a coded transmission is sent to
the central site database subsystem 12-5 to indicate that
25 processing was abandoned for this transmission.

When the dynamic selection subsystem 12-2 has
identified and selected data frames for further processing, a
control portion of this subsystem forwards the pairwise
identification of the frames to the signal processing
30 subsystem 12-3. For example, if data frames from six antenna
sites have been retained, these frames are identified as A,
B, C, D, E, and F. The control portion of the dynamic
selection subsystem 12-2 meters the pair combinations A-B,
A-C, A-D, etc., to the signal processing subsystem 12-3 until
35 all appropriate pair combinations have been completed.

-37-

Signal Processing Subsystem 12-3

The signal processing subsystem 12-3 is responsible for providing a time difference of arrival and frequency difference of arrival of a responsive transmission between

5 each pair of antenna site data frames forwarded by the dynamic control subsystem 12-2. The time difference of arrival indicates the difference in time between the arrival of the responsive transmission at a first antenna site and a second antenna site. The signal processing subsystem 12-3

10 attempts to estimate the time difference to better than 0.25 microsecond and preferably to better than 0.1 microsecond. The frequency difference of arrival indicates the perceived Doppler shift of the responsive transmission due to the motion of the transmitter relative to the fixed antenna

15 sites. The signal processing subsystem attempts to estimate the Doppler shift to better than 0.5 Hz and preferably to better than 0.1 Hz.

The estimation of the Doppler shift is generally affected by "chirp", which is inherent in the design of the

20 circuitry within the transmitter. Since the transmitters of primary interest emit bursty signals by definition, the transmitters must shift from a quiescent resting state to a transmitting state and then back to the resting state. As the internal circuits shift from the resting to the

25 transmitting states, the exact transmitting carrier frequency changes over time, eventually settling at the nominal frequency set by the transmitter. A small amount of chirp may also be caused by acceleration of the phone or by the modulation scheme used. These other sources are generally

30 minor compared to the chirp caused by the transmitter. As used herein, "chirp" is defined as a time varying derivative component of the signal's carrier as received at the antenna array.

In order to simultaneously estimate the time

35 difference (delay) and the frequency difference (Doppler) of the responsive signal while overcoming the effects of multipath, chirp, and other signal aberrations, the signal

processing subsystem 12-3 implements a maximum likelihood
estimation algorithm. Maximum likelihood algorithms have
been well studied in the art, and mathematically are
represented as the magnitude of the "Time-Frequency Cross
5 Correlation" function:

$$R_{x_1 x_2}(\tau, \Omega) = \left| \int_{-\infty}^{\infty} X_1(t-\tau) \, X_2^*(t) \, e^{-i\Omega t} dt \right|$$

where $X_1(t)$ and $X_2(t)$ are the complex envelopes of the
received signals:

$$X_1(t) = Re\{X_1(t) \, e^{i\omega_0 t}\}$$
$$X_2(t) = Re\{X_2(t) \, e^{i\omega_0 t}\}$$

In the above equations, τ represents the delay, Ω represents
Doppler shift, t represents time, ω_0 represents the frequency
10 of the responsive signal, $X_1(t)$ represents the complex
envelope of the responsive signal as received at a first
antenna site, $X_2(t)$ represents the complex envelope of the
responsive signal as received at a second antenna site, "Re"
represents the real portion the signal, and "$R_{x_1 x_2}$" is the
15 output of the function being maximized. In practice, the
integration need be performed only over the time period of
the responsive signal.

The exact implementation of this function in the
signal processor 12-3 is related to the signal structure of
20 the responsive signal. For example, the implementation may
vary for a cellular telephone, for a CDPD mobile unit, and
for a RAM Mobile Data unit. All implementations result in
the creation of a final output matrix, where the (i, j)
indices of the matrix represent possible estimates of the
25 delay τ and Doppler shift Ω values, and where the values
assigned to each cell in the matrix represent the value of
the magnitude of the "Time-Frequency Cross Correlation"
output function described above. The absolute peak of the

matrix is next determined, and then a fine interpolation is
performed to resolve possible better estimates of the delay
and Doppler shift that may occur between any discrete values
of i and j. The results of the fine interpolation are

5 assigned to the delay and Doppler shift for each antenna site
pair (i.e., A-B, A-C, A-D, etc.). The magnitude of the
output function is also determined along with the width of
the magnitude function at a predetermined point. The
magnitude, width, and quality factor determined by the multi-

10 antenna processing subsystem 10-3 (Fig. 2) are combined to
generate a new quality factor for the estimates of the delay
τ and Doppler shift Ω values. This quality factor is akin to
a statistical confidence interval measure. These three
values are forwarded to the position and speed determination

15 subsystem 12-4 (Fig. 4).

Position And Speed Determination Subsystem 12-4

The position and speed determination subsystem 12-4
is responsible for using the estimates of time difference of
arrival and frequency difference of arrival to calculate the

20 estimated geographic position, speed, and direction of travel
of the transmitter. In the position calculation, the
subsystem automatically incorporates Geographic Dilution of
Precision, or GDOP, into its estimation. Once the signal
processing subsystem 12-3 has processed data from all pairs

25 of antenna sites, the position and speed determination
subsystem creates a table indicating all processed antenna
sites and the calculated delay values and frequency values.

The position and speed determination subsystem 12-4
operates by performing a coarse estimate and then a fine

30 estimate. It first creates a grid of possible latitude and
longitude positions, at certain increments, which may be one-
half (1/2) minute for example. For each antenna site pair
for which data is available, the position and speed
determination subsystem calculates the theoretical delay

35 values from every point on the grid to each pair of antenna
sites. Then, at each point, the subsystem obtains the sum of
the squares of the observed delays minus the computed delays.

-40-

The coarse estimate is the point at which the sum of squares
is minimized. This least squares difference calculation
takes into account the quality factor determined earlier.
Therefore, the least squares difference equation takes the

5   form:

$$LSD = [Q_{12} (Delay\_T_{12}-Delay\_O_{12})^2 + Q_{13}(Delay\_T_{13}-Delay\_O_{13})^2 + \ldots + Q_{xy} (Delay\_T_{xy}-Delay\_O_{xy})^2]$$

where $Delay\_T_{xy}$ represents the theoretical delay between
antenna sites x and y, x and y being indices representative
10 of antenna sites; $Delay\_O_{xy}$ represents the observed delay
between antenna sites x and y; and Q_{xy} represents the quality
factor for the delay measurement between antenna sites x and
y.

From the coarse estimate, the subsystem refines the
15 estimate by performing a series of linearized-weighted-least-
squares iteration steps until the adjustment on each
iteration step is below some threshold, which may be 0.0001
degree for example. In a similar fashion, the position and
speed determination subsystem 12-4 estimates velocity (speed
20 and direction) by performing a grid search. Theoretical
frequency values are calculated rather than delays. However,
the process is otherwise analogous to the position
determination process. Typical thresholds used may be one
mile per hour and one degree of azimuth.

25 **Database Subsystem 12-5**

The database subsystem 12-5 is responsible for
storing customer, billing, and location information, and for
providing access to the location data to the various
applications discussed below. For example, if the location
30 system were locating cellular telephones, the database
subsystem would preferably contain the customers' name,
address, phone identification (MIN) and ESN for all phones
registered to the customer on the system, and the status of
various applications to which the customer may have
35 subscribed. For example, the customer may subscribe to a

-41-

cellular service whereby phone calls are rated (i.e., billed)
differently depending upon where the customer is located.
Alternatively, the customer may elect to inhibit the locating
of his telephone, and this election may be stored in the

5 database at the central site and the antenna sites. Location
processing may then be blocked for that customer. Whenever a
new transmitter is detected that has not been previously
registered in the database, that new transmitter is located
and then logged into the database automatically. For

10 example, if a "roaming" cellular telephone or other
transmitter enters the geographic area covered by the
location system, that telephone would automatically be
located and then entered into the database.

          The database subsystem 12-5 may be accessed locally

15 via terminals or may be accessed remotely by subscribers and
various applications. For example, a portable PC with
mapping software and CDPD functionality may access the
database to determine its own location. Alternately, a
dispatcher from a delivery company may access the database to

20 locate many packages or trucks. Because of the confidential
nature of the data stored in the database, the database
subsystem preferably incorporates various security measures
to prevent unauthorized access to data.

          The database subsystem 12-5 also stores historical

25 location information that can be used for billing customers
or for historical analysis. If, for example, the location
system operator desires to bill customers by the amount of
processing time used or location points processed, the
billing system can provide the location and time detail.

30 Alternatively, a bus transport company may desire to analyze
historical data to determine if the buses are operating on
efficient routes. Historical data may be automatically
archived after a period of time or, alternatively, the data
may be automatically purged from the system.

35   The database subsystem 12-5 can also store
electronic mapping data and then use this mapping data to
make adjustments to the estimated position. For example, if

the location system estimates the location of a transmitter
to be within a building and moving at 50 miles per hour, and
the mapping database knows that a highway runs within 100
feet of the building, the database may adjust the location
5 estimate to indicate that the transmitter is more likely to
be on the highway than in the building. This feature of
intelligently "snapping" the location estimate to a nearby
highway enables the database to serve Intelligent Vehicle
Highway Systems by providing crucial traffic data.

10 **IV.   Applications**
        There are a variety of commercially valuable
applications of the present invention. For example, in
addition to the basic function of tracking the location of a
mobile transmitter, the present invention may be employed to
15 offer location system subscribers billing rates that vary on
the basis of the location from which a transmission was made.
For example, a location tape, containing a record over time
of the locations of the subscribers' transmitter, may be
merged with a billing tape to produce a modified billing
20 tape. The billing tape contains data indicating the cost for
each transmission made within a certain time period. This
cost is based upon one or more predetermined billing rates.
The modified billing data is based upon a different rate for
transmissions made from certain specified locations.
25   The invention may also be employed to provide
emergency assistance, for example, in response to a "911"
call. In this application, the location system includes
means for automatically sending location information to a
specified receiving station in response to receiving a "911"
30 signal from a cellular telephone.
        Further, the invention may be employed in
connection with an alarm service. In this application, a
means is provided for comparing the current location of a
given transmitter with a specified range of locations and
35 indicating an alarm condition when the current location is
not within the prescribed range.

-43-

Yet another application involves detecting a lack
of signal transmissions by a given transmitter and in
response thereto automatically paging the transmitter to
cause it to initiate a signal transmission. This allows the
5   system to locate a transmitter that has failed to register
itself with the system. Such a feature could be used, for
example, to generate an alarm for subscribers at remote
locations.

Still another application involves estimating a
10 time of arrival of a given transmitter at a specified
location. This application is useful, for example, in
connection with a public transportation system to provide
estimated times of arrival of buses along established routes.

As mentioned above, the invention may also be
15 employed in locating packages in transit, wherein the
packages carry a small transmitting device like a cellular
telephone but not capable of voice communication.

The invention may also be employed in tracking
vehicles (cars, trucks, buses, trains, etc.), or even persons
20 (e.g., children or prisoners).

Further, the invention may be employed in
connection with an Intelligent Vehicle Highway System. In
such an application, the invention may include "snap-to"
functions on a map. That is, the location system would snap
25 the estimated point to the closest road on a map. In
connection with this or another application, a "confidence
interval" may be provided with the estimated point.

As described in detail in U.S. Patent Application
Serial No. 08/105,506, filed August 11, 1993, "Methods and
30 Apparatus for Increasing the Efficiency of a Cellular
Telephone Location System," the invention may be used to
create a Virtual Location Area unique to each transmitter.
For example, when a cellular telephone transmits on a reverse
control channel, the telephone location system would
35 determine the geographic position of the phone at that point
in time. Using the position and time as a starting point,

-44-

the system would determine a feasible location area for the
subscriber over some foreseeable time. This feasible
location area is designated a "Virtual Location Area" for
that telephone. The system would then determine which cell
5 sites cover that Virtual Location Area. If a call is placed
to that subscriber, the cellular system would page the
subscriber only over the forward control channels on the cell
sites covering that Virtual Location Area. Thus, the
invention allows the system to avoid needlessly using forward
10 control channel bandwidth in cell sites for which there is no
chance of reaching the subscriber.

-45-

We claim:

1.   A process for determining the location of a "standard" mobile transmitter not specifically designed or altered to provide signals facilitating the location of the
5   transmitter, said standard mobile transmitter being operative to receive a message signal and to respond to said message signal by transmitting a bursty responsive transmission indicative of the identity of the standard mobile transmitter, comprising the steps of:
10   (a)   receiving a bursty responsive transmission from said standard mobile transmitter at first, second, and third ground-based antenna sites;

            (b)   digitalizing the received bursty responsive transmission at each of said first, second, and third antenna
15   sites;

            (c)   determining first, second, and third time differences of arrival, said first time difference of arrival representing a difference between the time of arrival of said responsive transmission at said first and second antenna
20   sites, said second time difference of arrival representing a difference between the time of arrival of said responsive transmission at said first and third antenna sites, and said third time difference of arrival representing a difference between the time of arrival of said responsive transmission
25   at said second and third antenna sites; and

            (d)   estimating the location of said standard mobile transmitter on the basis of at least said first, second, and third time differences of arrival.

2.   A process as recited in claim 1, wherein said
30   standard mobile transmitter is a member of the group comprising a cellular telephone or transmitter, a personal communication network (PCN) transmitter, an enhanced specialized mobile radio (ESMR) transmitter, a cellular digital packet data (CDPD) transmitter, and a two-way packet-
35   based data transmitter.

-46-

3.   A process as recited in claim 2, wherein said
bursty responsive transmission is received over a messaging
channel.

4.   A process as recited in claim 3, wherein said
5 messaging channel is a control channel.

5.   A process as recited in claim 1 or claim 3,
further comprising the steps of:
(e)   determining first, second, and third frequency
differences of arrival, said first frequency difference of
10 arrival representing a difference between the frequency of
said responsive transmission as received at said first and
second antenna sites, said second frequency difference of
arrival representing a difference between the frequency of
said responsive transmission as received at said first and
15 third antenna sites, and said third frequency difference of
arrival representing a difference between the frequency of
said responsive transmission as received at said second and
third antenna sites; and
(f)   estimating the velocity of said standard
20 mobile transmitter on the basis of at least said first,
second, and third frequency differences of arrival.

6.   A process as recited in claim 1 or claim 3,
wherein the step of estimating the position of the mobile
transmitter comprises making a coarse estimate by creating a
25 grid of possible latitude and longitude positions for each
antenna site pair; calculating, for pairs of antenna sites,
theoretical time difference of arrival values from points on
the grid; determining a function of a sum of squares of the
measured time differences of arrival minus the computed time
30 differences of arrival; and coarsely estimating the position
as the point at which the function of the sum of squares is a
minimum.

7.   A process as recited in claim 6, wherein the
coarse estimation step further includes deriving quality
factors representing the quality of the signal received at
the antenna sites of said pairs, and the determination of the
5 function of the sum of squares includes weighting the squares
of the measured time differences of arrival minus the
computed time differences of arrival by the quality factor.

8.   A process as recited in claim 6, further
comprising providing a confidence interval along with the
10 location estimate, wherein said confidence interval defines
an area around the estimated location and there is a
probability the mobile transmitter is located within said
area.

9.   A process as recited in claim 5, wherein the
15 step of estimating the velocity of the mobile transmitter
comprises making a coarse estimate by creating a grid or
table of possible velocities; calculating, for pairs of
antenna sites, theoretical frequency difference of arrival
values corresponding to said possible velocities; determining
20 a function of a sum of squares of the measured frequency
differences of arrival minus the computed frequency
differences of arrival; and coarsely estimating the velocity
as the velocity at which the function of the sum of squares
is a minimum.

25   10.   A process as recited in claim 1 or claim 3,
further comprising generating a timing signal at each antenna
site and using said timing signal as a reference in
determining said time differences of arrival.

11.   A process as recited in claim 10, wherein the
30 generation of said timing signal comprises the steps of
receiving a global positioning system (GPS) signal and
generating a timing signal which is phase locked to said GPS
signal.

-48-

12. A process as recited in claim 10, wherein the generation of said timing signal comprises the steps of transmitting a modulated carrier from a central site, wherein the modulated carrier has a carrier frequency near the

5 frequency of the responsive signal; receiving said modulated carrier at each of said antenna sites; and using said modulated carrier as a reference signal for the generation of said timing signal.

13. A process as recited in claim 12, wherein the

10 modulation of said modulated carrier transmitted from the central site comprises a repetitive bit sequence having a repetition period greater than the greatest time difference of arrival expected to be encountered.

14. A process as recited in claim 12, wherein the

15 modulation of said modulated carrier transmitted from the central site comprises a pseudorandom bit sequence having a repetition rate greater than the greatest timing delay or time difference of arrival expected to be encountered.

15. A process as recited in claim 10, wherein the

20 generation of said timing signal comprises the steps of transmitting a reference signal from a plurality of reference transmitters, each reference transmitter being visible to a corresponding pair of antenna sites; receiving the reference signals at the respective antenna sites of each pair; and

25 using the reference signals, at each antenna site in each pair, in generating a timing signal having a frequency and phase matched to the frequency and phase of the timing signal of the other antenna site in that pair.

16. A process as recited in claim 15, wherein said

30 timing signal at each antenna site is an oscillating digital signal and is mixed with the digitalized responsive transmission or a downconverted version thereof to produce a baseband signal.

17. A process as recited in claim 1 or claim 3,
wherein the reception and processing of the responsive signal
at each antenna site comprises the steps of receiving the
responsive signal with an antenna array at each antenna site;
5 and providing a high quality signal for further processing.

18. A process as recited in claim 17, wherein the
step of providing a high quality signal comprises sampling a
signal from each antenna in said array and formatting the
samples into frames of digital data; and providing, on the
10 basis of the frames of data, a high quality digital baseband
signal for further processing.

19. A process as recited in claim 18, further
comprising determining whether the respective signals
received via the antennas of the array contain a prescribed
15 level of energy, and only providing a baseband signal for
those signals having said prescribed level of energy or
greater.

20. A process as recited in claim 19, wherein each
frame comprises a prescribed number of data bits and time
20 stamp bits that represent the time at which the responsive
signal was received.

21. A process as recited in claim 17, wherein the
high quality baseband signals are provided at the respective
antenna sites by coherently combining multiple baseband
25 signals so as to reduce the effects of multipath.

22. A process as recited in claim 21, further
comprising reducing the effects of multipath at each antenna
by detecting a first leading edge of said responsive signal
and rejecting subsequent leading edges of said responsive
30 signal.

-50-

23. A process as recited in claim 18, wherein the characteristics of the high quality baseband signal at the antenna sites include: (a) it represents a coherent combination of signals where possible; (b) envelope
5 variations have been removed; (c) phase and frequency have been faithfully maintained, and (d) timing bits in the signal reflect the measurement of the leading edge of the responsive signal at the antenna array.

24. A process as recited in claim 21, further
10 comprising the steps of:
(1) generating a substantially unimpaired representation of the baseband signal by remodulating a demodulated signal;
(2) determining which antenna in the array likely
15 received the transmission over the shortest and most direct path;
(3) performing a correlation between the generated, unimpaired representation of the signal and each of the signals received through each of the antennas, and
20 generating a correlation output function for each signal;
(4) determining the relative amount of multipath impairment that may have occurred at each antenna by measuring the width of each correlation output function at a predefined point on the correlation output function;
25   (5) coherently combining the signals that appear to have similar multipath impairments to increase the quality of the signal representation; and
(6) estimating a quality factor that is indicative of the relative amount of impairment that will remain in the
30 signal after processing.

25. A process as recited in claim 1 or claim 3, further comprising demodulating the responsive signal received at each antenna site, determining the identification of the mobile transmitter, and, on the basis of the

-51-

identification, deciding whether to further process or
discard the responsive signal.

26.   A process as recited in claim 25, further
comprising storing in a database a table indicating which
5 transmitters are to be located and which transmitters are not
to be located.

27.   A process as recited in claim 18, further
comprising extracting selected signal characteristics from
the high quality baseband signal; compressing the high
10 quality baseband signal so as to retain the selected
characteristics; and forwarding the compressed signal to a
prescribed location for further processing.

28.   A process as recited in claim 27, wherein the
selected characteristics include timing, power, frequency,
15 phase, and a factor representing the quality of the baseband
signal.

29.   A process as recited in claim 1 or claim 3,
wherein the time differences of arrival are determined using
a maximum likelihood estimator process.

20   30.   A process as recited in claim 29, wherein said
maximum likelihood estimator process involves finding the
peak of a function R_{x1x2} defined as,

$$R_{x_1 x_2}(\tau, \Omega) = \left| \int_{-\infty}^{\infty} X_1(t-\tau) \, X_2^{\circ}(t) \, e^{-i\Omega t} dt \right|$$

where $X_1(t)$ and $X_2(t)$ are the complex envelopes of the
received signals:

-52-

$$X_1(t) = Re\{X_1(t) e^{i\omega_o t}\}$$
$$X_2(t) = Re\{X_2(t) e^{i\omega_o t}\}$$

and τ represents the delay, Ω represents Doppler shift, t
represents time, ω_o represents the frequency of the
responsive signal, $X_1(t)$ represents the complex envelope of
the responsive signal as received at a first antenna site,
5   $X_2(t)$ represents the complex envelope of the responsive
signal as received at a second antenna site.

31.   A process as recited in claim 1 or claim 3,
wherein said time differences of arrival are determined using
digital signal processing.

10   32.   A process as recited in claim 5, wherein a
maximum likelihood estimator is employed to provide said
frequency differences of arrival and said time differences of
arrival.

33.   A process as recited in claim 32, further
15 comprising estimating and correcting for chirp.

34.   A process as recited in claim 1 or claim 3,
wherein the location estimation process involves dynamically
selecting the best data from all data generated by processing
data from the antenna site pairs.

20   35.   A process as recited in claim 34, wherein the
dynamic selection involves creating a table with data from
all available antenna site pairs and then ranking the antenna
site pairs in accordance with appropriate criteria.

36.   A process as recited in claim 35, further
25 comprising determining identification bits, a channel number,
and a time stamp for a signal obtained at each antenna site,
wherein the dynamic selection further comprises dynamically

-53-

organizing the data according to the identification bits, channel number, and time stamp.

37. A process as recited in claim 1 or claim 3, further comprising storing location, velocity, and
5 identification information in a remotely and locally accessible database.

38. A process as recited in claim 37, wherein the database allows storing, sorting, purging, and archiving of said information.

10   39. A process as recited in claim 38, further comprising preventing unauthorized access to location and identification information in said database.

40. A process as recited in claim 37, further comprising transforming data in said database into formats
15 compatible with an electronic mapping application.

41. A process as recited in claim 1 or claim 3, further comprising performing a calibration involving receiving, at multiple antenna sites, signals from a reference transmitter at a known location, and then
20 performing measurements among pairs of antenna sites to determine systemic errors that may exist.

42. A process as recited in claim 41, wherein the calibration produces a site bias for use in location and velocity calculations.

25   43. A process as recited in claim 1 or claim 3, further comprising merging the location data with billing data for said mobile transmitter, and generating modified billing data, wherein said billing data indicates the cost for each transmission made by said transmitter within a
30 certain time period, said cost being based upon one or more

-54-

predetermined billing rates, and said modified billing data
is based upon a different rate for calls made from one or
more prescribed locations.

44. A process as recited in claim 1 or claim 3,
5 further comprising transmitting a signal to a selected mobile
transmitter to cause said selected transmitter to transmit.

45. A process as recited in claim 1 or claim 3,
further comprising automatically sending location information
to a prescribed receiving station in response to receiving a
10 distress signal from a mobile transmitter, whereby emergency
assistance may be provided to a subscriber in distress.

46. A process as recited in claim 1 or claim 3,
further comprising comparing the current location of a given
mobile transmitter with a prescribed range of locations and
15 indicating an alarm condition when said current location is
not within said prescribed range.

47. A process as recited in claim 1 or claim 3,
further comprising detecting a lack of signal transmissions
by a given mobile transmitter and in response thereto
20 automatically paging said given transmitter to cause said
given transmitter to initiate a transmission.

48. A process as recited in claim 1 or claim 3,
further comprising detecting a lack of signal transmissions
by a given mobile transmitter and in response thereto
25 automatically generating an alarm.

49. A process as recited in claim 1 or claim 3,
further comprising estimating a time of arrival of a given
transmitter at a prespecified location.

-55-

50.   A process as recited in claim 1 or claim 3,
comprising locating an object or person carrying said mobile
transmitter.

51.   A process as recited in claim 1 or claim 3,
5 further comprising determining whether the estimated location
is a feasible location and, if not feasible, setting or
"snapping" the estimated location to the nearest feasible
location.

52.   A process as recited in claim 1 or claim 3,
10 further comprising determining a feasible location area, or
Virtual Location Area, for the mobile transmitter and sending
messages to the transmitter only from antenna sites covering
the Virtual Location Area.

53.   A system for determining the location of a
15 "standard" mobile transmitter not specifically designed or
altered to provide signals facilitating the location of the
transmitter, said standard mobile transmitter being operative
to receive a message signal and to respond to said message
signal by transmitting a bursty responsive transmission
20 indicative of the identity of the standard mobile
transmitter, comprising:
         (a)   means for receiving a bursty responsive
transmission from said standard mobile transmitter at first,
second, and third antenna sites;
25   (b)   means for digitalizing the received bursty
responsive transmission at each of said first, second, and
third ground-based antenna sites;
         (c)   means for determining first, second, and third
time differences of arrival, said first time difference of
30 arrival representing a difference between the time of arrival
of said responsive transmission at said first and second
antenna sites, said second time difference of arrival
representing a difference between the time of arrival of said
responsive transmission at said first and third antenna

-56-

sites, and said third time difference of arrival representing
a difference between the time of arrival of said responsive
transmission at said second and third antenna sites; and

(d)   means for estimating the location of said
5   standard mobile transmitter on the basis of at least said
first, second, and third time differences of arrival.

54. A system as recited in claim 53, wherein said
standard mobile transmitter is a member of the group
comprising a cellular telephone, a personal communication
10   network (PCN) transmitter, an enhanced specialized mobile·
radio (ESMR), a cellular digital packet data (CDPD)
transmitter, and a two-way packet-based data transmitter.

55. A system as recited in claim 54, wherein said
bursty responsive transmission is received over a messaging
15   channel.

56. A system as recited in claim 55, wherein said
messaging channel is a control channel.

57. A system as recited in claim 53 or claim 55,
further comprising:
20   (e)   means for determining first, second, and third
frequency differences of arrival, said first frequency
difference of arrival representing a difference between the
frequency of said responsive transmission as received at said
first and second antenna sites, said second frequency
25   difference of arrival representing a difference between the
frequency of said responsive transmission as received at said
first and third antenna sites, and said third frequency
difference of arrival representing a difference between the
frequency of said responsive transmission as received at said
30   second and third antenna sites; and
(f)   means for estimating the velocity of said
standard mobile transmitter on the basis of at least said
first, second, and third frequency differences of arrival.

-57-

58. A system as recited in claim 53 or claim 55,
wherein the means for estimating the position of the mobile
transmitter comprises means for making a coarse estimate by
creating a grid of possible latitude and longitude positions
5 for each antenna site pair; calculating, for pairs of antenna
sites, theoretical time difference of arrival values from
points on the grid; determining a function of a sum of
squares of the measured time differences of arrival minus the
computed time differences of arrival; and coarsely estimating
10 the position as the point at which the function of the sum of
squares is a minimum.

59. A system as recited in claim 58, wherein the
means for making a coarse estimation further includes means
for deriving quality factors representing the quality of the
15 signal received at the antenna sites of said pairs, and
weighting the squares of the measured time differences of
arrival minus the computed time differences of arrival by the
quality factor.

60. A system as recited in claim 58, further
20 comprising means for providing a confidence interval along
with the location estimate, wherein said confidence interval
defines an area around the estimated location and there is a
probability the mobile transmitter is located within said
area.

25   61. A system as recited in claim 57, wherein the
means for estimating the velocity of the mobile transmitter
comprises means for making a coarse estimate by creating a
grid of possible velocities; calculating, for pairs of
antenna sites, theoretical frequency difference of arrival
30 values from points on the grid; determining a function of a
sum of squares of the measured frequency differences of
arrival minus the computed frequency differences of arrival;
and coarsely estimating the velocity as the velocity at which
the function of the sum of squares is a minimum.

62. A system as recited in claim 53 or claim 55,
further comprising means for generating a timing signal at
each antenna site and using said timing signal as a reference
in determining said time differences of arrival.

5   63. A system as recited in claim 62, wherein the
means for generating a timing signal comprises means for
receiving a global positioning system (GPS) signal and
generating a timing signal which is phase locked to said GPS
signal.

10   64. A system as recited in claim 62, wherein the
means for generating a timing signal comprises means for
transmitting a modulated carrier from a central site, wherein
the modulated carrier has a carrier frequency near the
frequency of the responsive signal; means for receiving said
15 modulated carrier at each of said antenna sites; and means
for using said modulated carrier as a reference signal for
the generation of said timing signal.

65. A system as recited in claim 64, wherein the
modulation of said modulated carrier transmitted from the
20 central site comprises a repetitive bit sequence having a
repetition period greater than the greatest time difference
of arrival expected to be encountered.

66. A system as recited in claim 64, wherein the
modulation of said modulated carrier transmitted from the
25 central site comprises a pseudorandom bit sequence having a
repetition rate greater than the greatest timing delay or
time difference of arrival expected to be encountered.

67. A system as recited in claim 62, wherein the
means for generating a timing signal comprises means for
30 transmitting a reference signal from a plurality of reference
transmitters, each reference transmitter being visible to a
corresponding pair of antenna sites; means for receiving the

-59-

reference signals at the respective antenna sites of each
pair; and means for using the reference signals, at each
antenna site in each pair, in generating a timing signal
having a frequency and phase matched to the frequency and
5   phase of the timing signal of the other antenna site in that
pair.

        68. A system as recited in claim 67, wherein said
timing signal at each antenna site is an oscillating digital
signal and is mixed with the digitalized responsive
10 transmission or a downconverted version thereof to produce a
baseband signal.

        69. A system as recited in claim 53 or claim 55,
comprising an antenna array at each antenna site and means
for providing a high quality signal for further processing at
15 each antenna site.

        70. A system as recited in claim 69, wherein the
means for providing a high quality signal comprises means for
sampling a signal from each antenna in said array and
formatting the samples into frames of digital data, and
20 providing, on the basis of the frames of data, a high quality
digital baseband signal for further processing.

        71. A system as recited in claim 70, further
comprising means for determining whether the respective
signals received via the antennas of the array contain a
25 prescribed level of energy, and only providing a baseband
signal for those signals having said prescribed level of
energy or greater.

        72. A system as recited in claim 71, wherein each
frame comprises a prescribed number of data bits and time
30 stamp bits that represent the time at which the responsive
signal was received.

73. A system as recited in claim 70, wherein the
high quality baseband signals are provided at the respective
antenna sites by coherently combining multiple baseband
signals so as to reduce the effects of multipath.

5   74. A system as recited in claim 73, further
comprising means for reducing the effects of multipath at
each antenna by detecting a first leading edge of said
responsive signal and rejecting subsequent leading edges of
said responsive signal.

10   75. A system as recited in claim 70, wherein the
characteristics of the high quality baseband signal at the
antenna sites include: (a) it represents a coherent
combination of signals where possible; (b) envelope
variations have been removed; (c) phase and frequency have
15 been faithfully maintained, and (d) timing bits in the signal
reflect the measurement of the leading edge of the responsive
signal at the antenna array.

76. A system as recited in claim 73, further
comprising means for:
20   (1) generating a substantially unimpaired
representation of the baseband signal by remodulating a
demodulated signal;
            (2) determining which antenna in the array likely
received the transmission over the shortest and most direct
25 path;
            (3) performing a correlation between the
generated, unimpaired representation of the signal and each
of the signals received through each of the antennas, and
generating a correlation output function for each signal;
30   (4) determining the relative amount of multipath
impairment that may have occurred at each antenna by
measuring the width of each correlation output function at a
predefined point on the correlation output function;

-61-

(5)   coherently combining the signals that appear
to have similar multipath impairments to increase the quality
of the signal representation; and

(6)   estimating a quality factor that is indicative
5 of the relative amount of impairment that will remain in the
signal after processing.

77. A system as recited in claim 53 or claim 55,
further comprising means for demodulating the responsive
signal received at each antenna site, determining the
10 identification of the mobile transmitter, and, on the basis
of the identification, deciding whether to further process or
discard the responsive signal.

78. A system as recited in claim 77, further
comprising a database for storing a table indicating which
15 transmitters are to be located and which transmitters are not
to be located.

79. A system as recited in claim 70, further
comprising means for extracting selected signal
characteristics from the high quality baseband signal;
20 compressing the high quality baseband signal so as to retain
the selected characteristics; and forwarding the compressed
signal to a prescribed location for further processing.

80. A system as recited in claim 79, wherein the
selected characteristics include timing, power, frequency,
25 phase, and a factor representing the quality of the baseband
signal.

81. A system as recited in claim 53 or claim 55,
wherein the time differences of arrival are determined using
a maximum likelihood estimator process.

-62-

82. A system as recited in claim 81, wherein said maximum likelihood estimator process involves finding the peak of a function R_{x1x2} defined as,

$$R_{x_1 x_2}(\tau, \Omega) = \left| \int_{-\infty}^{\infty} X_1(t-\tau) \, X_2^*(t) \, e^{-i\Omega t} dt \right|$$

where $X_1(t)$ and $X_2(t)$ are the complex envelopes of the
5　received signals:

$$X_1(t) = Re\{X_1(t) e^{i\omega_o t}\}$$
$$X_2(t) = Re\{X_2(t) e^{i\omega_o t}\}$$

and τ represents the delay, Ω represents Doppler shift, t represents time, ω_o represents the frequency of the responsive signal, $X_1(t)$ represents the complex envelope of the responsive signal as received at a first antenna site,
10　$X_2(t)$ represents the complex envelope of the responsive signal as received at a second antenna site.

83. A system as recited in claim 53 or claim 55, wherein said time differences of arrival are determined using digital signal processing.

15　　　　84. A system as recited in claim 57, comprising means for employing a maximum likelihood estimator to provide said frequency differences of arrival.

85. A system as recited in claim 84, further comprising means for estimating and correcting for chirp.

20　　　　86. A system as recited in claim 53 or claim 55, further comprising means for dynamically selecting the best data from all data generated by processing data from the antenna site pairs.

87. A system as recited in claim 86, wherein the dynamic selection involves creating a table with data from all available antenna site pairs and then ranking the antenna site pairs in accordance with appropriate criteria.

5   88. A system as recited in claim 87, further comprising means for determining identification bits, a channel number, and a time stamp for a signal obtained at each antenna site, wherein the dynamic selection further comprises dynamically organizing the data according to the
10   identification bits, channel number, and time stamp.

89. A system as recited in claim 53 or claim 55, further comprising a remotely and locally accessible database for storing location, velocity, and identification information.

15   90. A system as recited in claim 89, wherein the database allows storing, sorting, purging, and archiving of said information.

91. A system as recited in claim 89, further comprising means for preventing unauthorized access to
20   location and identification information in said database.

92. A system as recited in claim 89, further comprising means for transforming data in said database into formats compatible with an electronic mapping application.

93. A system as recited in claim 53 or claim 55,
25   further comprising means for performing a calibration involving receiving, at multiple antenna sites, signals from a reference transmitter at a known location, and then performing measurements among pairs of antenna sites to determine systemic errors that may exist.

94. A system as recited in claim 93, wherein the calibration produces a site bias for use in location and velocity calculations.

95. A system as recited in claim 53 or claim 55, further comprising means for merging the location data with billing data for said mobile transmitter, and generating modified billing data, wherein said billing data indicates the cost for each transmission made by said transmitter within a certain time period, said cost being based upon one or more predetermined billing rates, and said modified billing data is based upon a different rate for calls made from one or more prescribed locations.

96. A system as recited in claim 53 or claim 55, further comprising means for transmitting a signal to a selected mobile transmitter to cause said selected transmitter to transmit.

97. A system as recited in claim 53 or claim 55, further comprising means for automatically sending location information to a prescribed receiving station in response to receiving a distress signal from a mobile transmitter, whereby emergency assistance may be provided to a subscriber in distress.

98. A system as recited in claim 53 or claim 55, further comprising means for comparing the current location of a given mobile transmitter with a prescribed range of locations and indicating an alarm condition when said current location is not within said prescribed range.

99. A system as recited in claim 53 or claim 55, further comprising means for detecting a lack of signal transmissions by a given mobile transmitter and in response thereto automatically paging said given transmitter to cause said given transmitter to initiate a transmission.

100. A system as recited in claim 53 or claim 55, further comprising detecting a lack of signal transmissions by a given mobile transmitter and in response thereto automatically generating an alarm.

5   101. A system as recited in claim 53 or claim 55, further comprising means for estimating a time of arrival of a given transmitter at a prespecified location.

102. A system as recited in claim 53 or claim 55, comprising means for locating an object or person carrying
10 said mobile transmitter.

103. A system as recited in claim 53 or claim 55, further comprising means for determining whether the estimated location is a feasible location and, if not feasible, setting or "snapping" the estimated location to the
15 nearest feasible location.

104. A system as recited in claim 53 or claim 55, further comprising means for determining a feasible location area, or Virtual Location Area, for the mobile transmitter and sending messages to the transmitter only from antenna
20 sites covering the Virtual Location Area.

105. A system for determining the location of a "standard" mobile transmitter not specifically designed or altered to provide signals facilitating the location of the transmitter, said standard mobile transmitter being operative
25 to receive a message signal and to respond to said message signal by transmitting a bursty responsive transmission indicative of the identity of the standard mobile transmitter, comprising:
        (a)   at least three ground-based antenna site
30 systems, each antenna site system comprising: an antenna; a sampling subsystem operatively coupled to said antenna for sampling said bursty responsive signal at a prescribed

sampling frequency and formatting the sampled signal into
frames of digital data, each frame comprising a prescribed
number of data bits and time stamp bits, said time stamp bits
representing the time at which said bursty responsive
5   transmission was received; a baseband convertor operatively
coupled to said sampling subsystem for providing baseband
signals derived from said frames of data; and a timing
subsystem operatively coupled to said sampling subsystem for
providing timing signals; and
10   (b)   a central site system operatively coupled to
said antenna site systems, comprising means for processing
said frames of data to generate data identifying said mobile
transmitter and the differences in times of arrival of said
responsive signal among said antenna site systems; and means
15   for determining, on the basis of said times of arrival
differences, the location of the mobile transmitter.

        106. A system as recited in claim 105, wherein said
timing subsystem comprises a global positioning system (GPS)
receiver.

20   107. A system as recited in claim 105, further
comprising a central transmitter for transmitting a timing
signal comprising a modulated carrier, wherein said timing
subsystem comprises a receiver for receiving said timing
signal.

25   108. A system as recited in claim 105, further
comprising a plurality of reference transmitters, each
reference transmitter being visible to at least a
corresponding pair of antenna site systems; and wherein the
timing subsystem associated with each antenna site system of
30   a pair comprises means for receiving a reference signal from
a corresponding reference transmitter and outputting a timing
signal whose frequency and phase are matched to the frequency
and phase output by the timing subsystem of the other antenna
site system in that pair.

109. A system as recited in claim 105, wherein said central site system comprises a maximum likelihood estimator for determining time differences of arrival and frequency differences of arrival.

110. A system as recited in claim 105, comprising location estimation means for:

(1) creating a grid of theoretical points covering a prescribed geographic area, said theoretical points being spaced at prescribed increments of latitude and longitude;

(2) calculating theoretical values of time delay for a plurality of pairs of antenna sites;

(3) calculating a least squares difference value based on the theoretical time delays and measured time delays for a plurality of pairs of antenna sites;

(4) searching the grid of theoretical points and determining the best theoretical latitude and longitude for which the value of the least squares difference is minimized; and

(5) starting at the best theoretical latitude and longitude, performing another linearized-weighted-least-squares iteration to resolve the actual latitude and longitude to within a prescribed number of degrees or fraction of a degree.

111. A system as recited in claim 105, wherein said calculating step (2) comprises accounting for any known site biases caused by mechanical, electrical, or environmental factors, said site biases determined by periodically calculating the positions of reference transmitters at known locations.

112. A system as recited in claim 105, wherein said least squares difference is given by:

$$LSD = [Q_{12}(Delay\_T_{12}-Delay\_O_{12})^2 + Q_{13}(Delay\_T_{13}-Delay\_O_{13})^2 + \ldots Q_{xy}(Delay\_T_{xy}-Delay\_O_{xy})^2]$$

where, $Delay\_T_{xy}$ represents the theoretical delay between
antenna sites x and y, x and y being indices representative
of antenna sites; $Delay\_O_{xy}$ represents the observed delay
between antenna sites x and y; Q_{xy} represents a quality
5   factor for the delay measurement between antenna sites x and
y, said quality factor being an estimated measure of the
degree to which multipath or other anomalies may have
affected a particular delay measurement.

113. A system as recited in claim 105, further
10 comprising means for detecting a first leading edge of said
responsive signal and rejecting subsequent leading edges of
said responsive signal, whereby the effects of multipath may
be reduced.

114. A system as recited in claim 105, comprising
15 velocity estimation means for:
    (1)   creating a grid of theoretical points covering
a prescribed range of velocities, said theoretical points
being spaced at prescribed increments;
    (2)   calculating theoretical values of frequency
20 difference for a plurality of pairs of antenna sites;
    (3)   calculating a least squares difference value
based on the theoretical frequency differences and measured
frequency differences for a plurality of pairs of antenna
sites;
25   (4)   searching the entire grid of theoretical
points and determining the best theoretical velocity for
which the value of least squares difference is minimized; and
    (5)   starting at the best theoretical velocity,
performing another linearized-weighted-least-squares
30 iteration to resolve the actual velocity to within a
prescribed tolerance.

115. A system as recited in claim 105, further
comprising a database for storing transmitter identification
and location data.

116. A system as recited in claim 105, further comprising means for transmitting a signal to said mobile transmitter to cause said mobile transmitter to transmit said responsive signal over a messaging channel.

5   117. A method for determining the location of a mobile transmitter operative to receive a message signal and to respond to said message signal by transmitting a responsive signal over a predefined messaging channel, said responsive signal being indicative of the identity of the

10 mobile transmitter, comprising the steps of:
        (a)   receiving said signal at at least three separate ground-based antenna sites;
        (b)   processing said signal at each antenna site to produce frames of data, each frame comprising a prescribed

15 number of data bits and time stamp bits, said time stamp bits representing the time at which said frames were produced at each antenna site;
        (c)   processing said frames of data to identify said responsive signal and the differences in times of

20 arrival of said responsive signal among said antenna sites; and
        (d)   determining, on the basis of said times of arrival differences, the location of said mobile transmitter.

118. A method as recited in claim 117, further
25 comprising the steps of storing location data identifying the mobile transmitter and its location, and providing access to said location data to subscribers at remote locations.

119. A method as recited in claim 117, further comprising transmitting a signal to said mobile transmitter
30 to cause said mobile transmitter to transmit a responsive signal over a messaging channel.

120. A method as recited in claim 117, further comprising merging the location data with billing data for

said mobile transmitter, and generating modified billing
data, wherein said billing data indicates the cost for each
transmission made by said transmitter within a certain time
period, said cost being based upon one or more predetermined
5   billing rates, and said modified billing data is based upon a
different rate for calls made from one or more prescribed
locations.

       121. A method as recited in claim 117, comprising
estimating the location of said mobile transmitter by
10 performing the following steps:
              (1)   creating a grid of theoretical points covering
a prescribed geographic area, said theoretical points being
spaced at prescribed increments of latitude and longitude;
              (2)   calculating theoretical values of time delay
15 for a plurality of pairs of antenna sites;
              (3)   calculating a least squares difference (LSD)
value based on the theoretical time delays and measured time
delays for a plurality of pairs of antenna sites;
              (4)   searching the entire grid of theoretical
20 points and determining the best theoretical latitude and
longitude for which the value of LSD is minimized; and
              (5)   starting at the best theoretical latitude and
longitude, performing another linearized-weighted-least-
squares iteration to resolve the actual latitude and
25 longitude to within a prescribed number of degrees or
fraction of a degree.

       122. A method as recited in claim 117, wherein said
calculating step (2) comprises accounting for any known site
biases caused by mechanical, electrical, or environmental
30 factors, said site biases determined by periodically
calculating the positions of reference transmitters at known
locations.

       123. A method as recited in claim 121, wherein said
least squares difference is given by:

-71-

$$LSD = \sum Q_{xy}(Delay\_T_{xy} - Delay\_O_{xy})^2$$

where, Delay_T$_{xy}$ represents the theoretical delay between
antenna sites x and y, x and y being indices representative
of antenna sites; Delay_O$_{xy}$ represents the observed delay
5 between antenna sites x and y; Q$_{xy}$ represents a quality
factor for the delay measurement between antenna sites x and
y, said quality factor being an estimated measure of the
degree to which multipath or other anomalies may have
affected a particular delay measurement.

10   124. A method as recited in claim 117, further
comprising detecting a first leading edge of said responsive
signal and rejecting subsequent leading edges of said
responsive signal.

          125. A method as recited in claim 117, comprising
15 estimating the velocity of said mobile transmitter by
performing the following steps:
          (1)   creating a grid of theoretical points covering
a prescribed range of velocities, said theoretical points
being spaced at prescribed increments;
20   (2)   calculating theoretical values of frequency
difference for a plurality of pairs of antenna sites;
          (3)   calculating a least squares difference (LSD)
value based on the theoretical frequency differences and
measured frequency differences for a plurality of pairs of
25 antenna sites;
          (4)   searching the entire grid of theoretical
points and determining the best theoretical velocity for
which the value of LSD is minimized; and
          (5)   starting at the best theoretical velocity,
30 performing another linearized-weighted-least-squares
iteration to resolve the actual velocity to within a
prescribed tolerance.

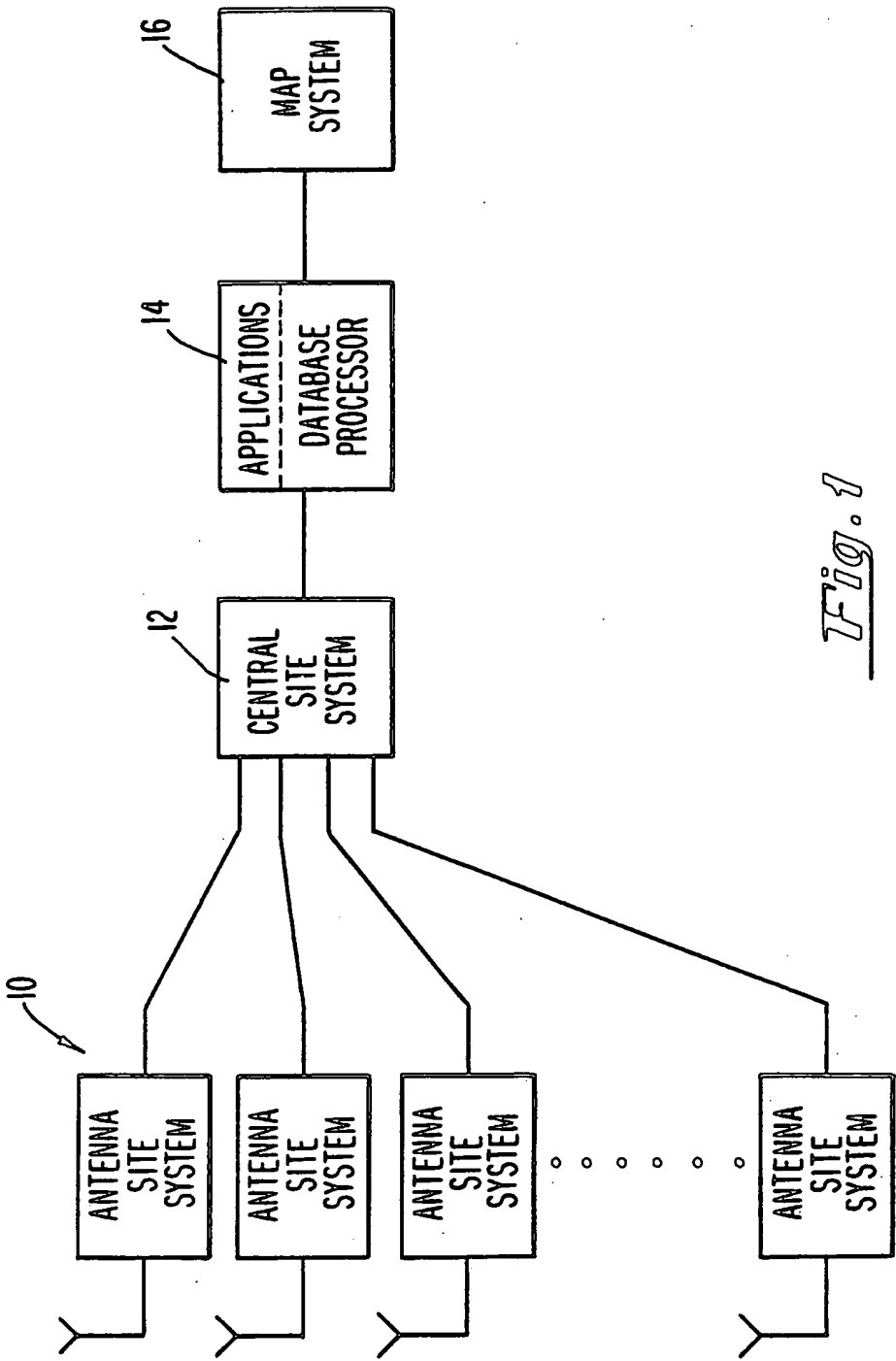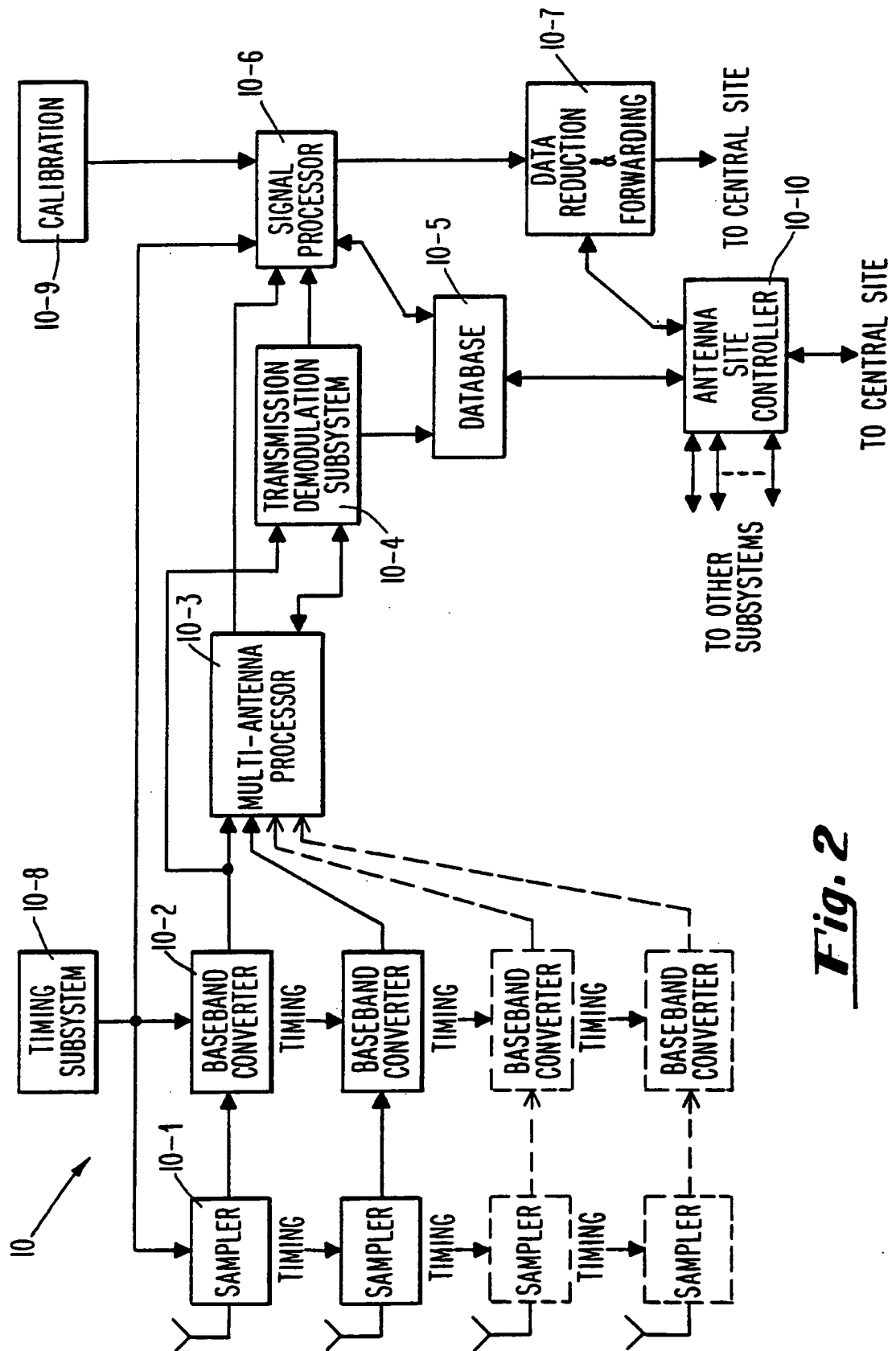126. A method as recited in claim 117, comprising locating an object or person carrying said mobile transmitter.

Fig. 1

Fig. 2

Fig. 3

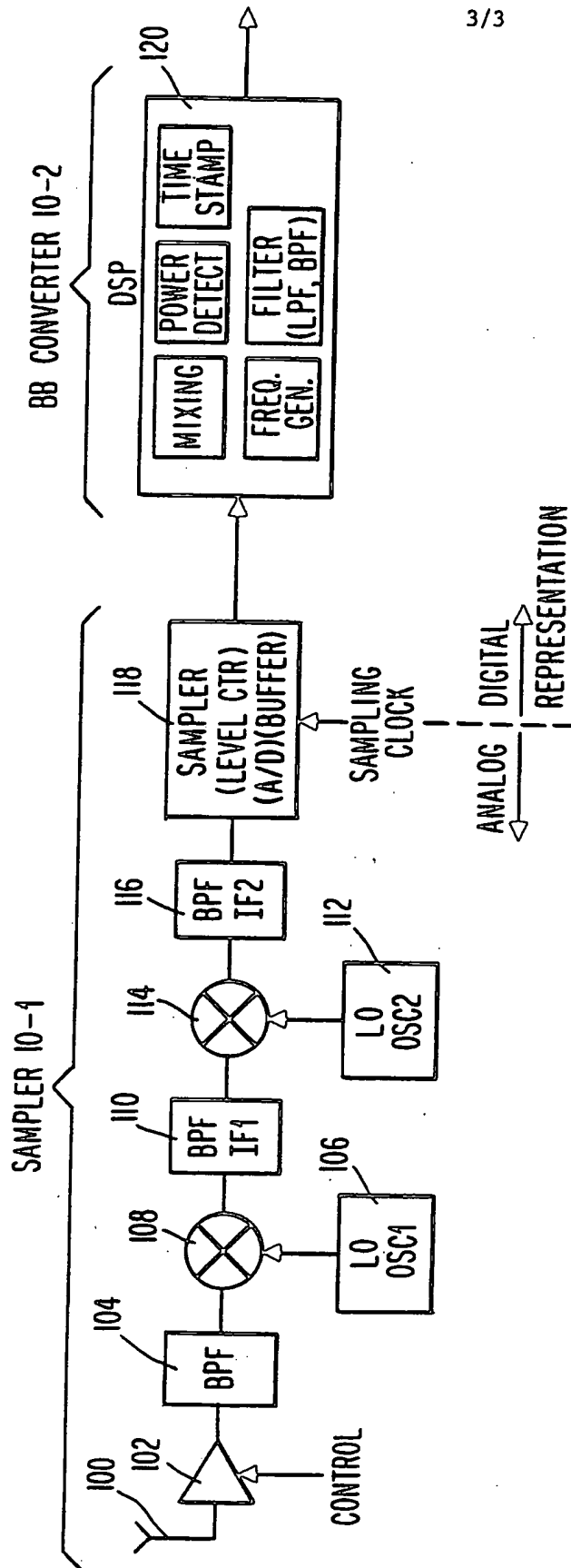Fig. 4
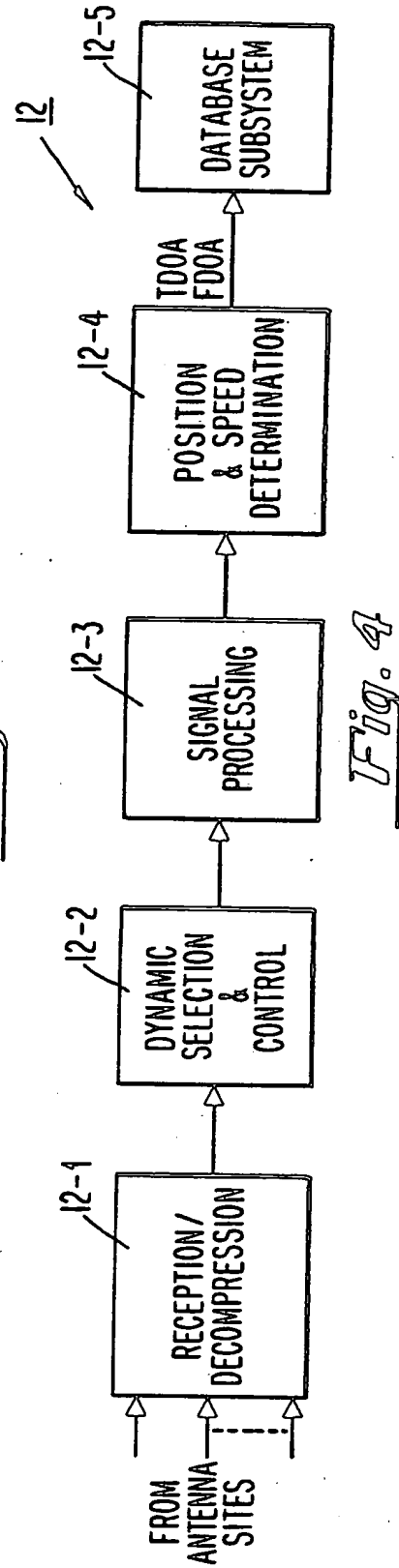
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :G01S 1/24, 3/02; HO4M 11/00
US CL : 342/387, 457; 379/58

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. 342/387, 457, 357; 379/58

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 3,150,372(GROTH, JR) 22 SEPTEMBER 1964, SEE FIGURE 1	1-126
Y	IEEE TRANS. ON AEROSPACE AND ELECTRONIC SYSTEMS, VOL. AES-18, NO. 2, MARCH 1982, CHESTNUT, "EMITTER LOCATION ACCURACY USING TDOA AND DIFFERENTIAL DOPPLER", P. 214-219. SEE ENTIRE DOCUMENT	1-126
Y	US, A, 4,433,335 (WIND) 21 FEBRUARY 1984, SEE FIGURE 3.	1-126
X	US, A, 5,191,342 (ALSUP ET AL) 02 MARCH 1993, SEE FIGURE 5.	1,53,105,117
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Y		2-52,54 - 104,106-116, 118-126

[X] Further documents are listed in the continuation of Box C.   [ ] See patent family annex.

Special categories of cited documents:

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
01 AUGUST 1994	**19 AUG 1994**

Name and mailing address of the ISA/US	Authorized officer
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Form PCT/ISA/210 (second sheet)(July 1992)*

C. (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,E ----- Y	US, A, 5,317,323 (KENNEDY ET AL) 31 MAY 1994, SEE ENTIRE DOCUMENT	1,53,105,117 ------------- 2-52, 54-104, 106-116, 118-126